A STUDY OF THE MIXING OF FEEDING STUFFS WITH SPECIAL REFERENCE TO UNIFORMITY OF THE PRODUCT

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SUMMARY OF THE STUDY

The factors affecting the mixing of meals were discussed in the light of previous work and relationships were developed for experimental study. Particle size characteristics were investigated by sieving and microscopic examination in order to determine the specific surface of meals which was a measure of inter-facial mixability. Porosity of meals was important because air was the flow medium; the rate of flow depended upon viscosity and a pipe viscometer was constructed for its measurement. Viscosity of meals was a function of particle size, specific surface, apparent density, angle of repose, porosity and moisture content. The greater the viscosity of meals the longer the time to reach uniformity.

The uniformity of a meal was measured by its uniformity index, a statistical value that ranged from unity for complete unmixedness to zero for complete uniformity. It was obtained by sampling and analysing for specific mix components. The composition of a mix affected its rate of mixing; generally speaking, the greater the number of ingredients and the closer the ingredient proportions the slower the mixing rate. The mixing process proceeded according to an exponential equation which differed for each mix.

Mixing ability was tested in a half-size model mixer, but it could represent full-scale mixing by introducing scale constants. The design features that were varied included the in-feed position, mixing chamber size, and auger speed and arrangement; the greatest uniformity was attained with the top-feed version of the mixer with a mixing chamber depth two-thirds its diameter, an auger speed of 175 r.p.m. and the fitting of an auger shroud and spreading blades. The mixing time for complete uniformity according to the mixing equations, varied between 40 and 100 minutes, but no mix achieved this state in practice. This observation indicated that, either normal mixing times were too short, or that the mixer design was inadequate.

The study was concluded with a feeding experiment which indicated that a non-uniform mix retarded the growth rate of pigs.

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NOTATION

The following notation is used throughout the thesis and the symbols are the conventional ones except where duplications occur or where they are unsuitable for the typewriter.

a = area
b = breadth
c = constant
d = diameter
d_a = arithmetic mean diameter
d_g = geometric mean diameter
d_h = harmonic mean diameter
d_i = length mean diameter
d_m = median diameter
d_n = diameter of an equivalent sphere
d_p = mean projected diameter
d_s = surface mean diameter
d_v = volume mean diameter
d_{vs} = volume-surface mean diameter
d_w = weight mean diameter
e = exponential
f = surface coefficient of particles
g = gravitational acceleration
h = flakiness
i = index
k = constant
m = mass
n = elongation
p = density
p_a = apparent density
p_f = fluid density
r_o = radius
s = standard deviation
t = time
u = coefficient of viscosity
u_k = coefficient of kinematic viscosity
v = velocity
v = centrifugal settling velocity
w = weight
x = proportion
$\bar{x}$ = mean proportion

A = side of a square aperture
B = bulkiness
C = volume coefficient of particles
C_e = volume coefft. of equi-dimensional
C_r = coefficient of resistance
D = orifice diameter
F = Froude Number
F.M. = Fineness Modulus
G_v = volume shape factor
H_o = statistical hypothesis
L = length
L_m = scale length for model
M = moisture content
N = number
P = porosity
Q = quantity
R = Reynold's number
S = specific surface of particles
T = thickness
U = uniformity index
U_o = uniformity of unmixed batch
U_c = criterion of uniformity
U_z = uniformity of all components of a batch
U.M. = uniformity modulus
V = voids
W = angular velocity
X = percentage
Y = angle of repose
π = circular constant
Σ = sum

1. INTRODUCTION.

OBJECTS OF THE STUDY.

1.1 The mixing of animal feeding stuffs had not been investigated to the same extent as the mixing of liquids, chemicals and other industrial materials, therefore, this was an attempt to determine and analyse the factors that affected a process for which few fundamental principles existed. Since the object of mixing was to produce as uniform a blend of a series of ingredients as possible, the main object of this study was to relate the factors affecting the mixing process with the uniformity of the final product. It was realised that the subject was very complex and that a complete study of all its aspects would be beyond the scope of this work, however, an attempt was made to lay down foundations from which further specific investigations could be developed.

The basic objects of the study are summarized as follows:-

(1) To study information relating to all forms of mixing, with special reference to those factors which influence the process and the uniformity of the product.

(2) To discuss and classify the information obtained above with respect to the mixing of animal feeding stuffs.

(3) To examine the effect on the mixing process on the physical and mechanical properties of the meals that compose feeding stuffs.

(4) To develop and test a procedure for assessing the uniformity of mixing.

(5) To examine experimentally the effect of the properties of meals on the uniformity of mixing.

(6) To construct an experimental mixer in order to study the effect of mixer design factors on the uniformity of mixing.

(7) To study the effect of mix composition factors, such as number and proportions of components, on the uniformity of mixing.

(8) To examine the effect of feeding non-uniform feeding stuffs.

(9) To discuss and summarize the information obtained during the course of this study.

FACTORS INFLUENCING MIXING.

The mixing of feeding stuffs is a process by which a variable number of

ingredients are blended together so that the resultant mixture provides the correct ration for specific feeding purposes. It is most important that the ingredients be uniformly mixed in the correct proportions to prevent variation in the constitution of samples from the mixture.

The factors that influence the effectiveness of mixing can be classified under two headings as follows:-

1.2 Factors arising from the ingredients of the mixture.

(a) Number of ingredients.
(b) Variety of the ingredients.
(c) Quantity of the mixture.
(d) Proportions of the ingredients in the mixture.
(e) Physical properties of the ingredients.
(f) Mechanical properties of the ingredients.

1.3 Factors arising from the mixing process.

(a) Method of mixing.
(b) Rate of mixing.
(c) Design of the mixing machine.
(d) Operation of the mixing machine.

The expansion of these headings is necessary to develop the lines of approach for research into mixing. Fundamentals have been established for mixing liquids and homogeneous solid particles, but the majority of the constituents of animal feeding stuffs are heterogeneous, both physically and chemically. Consequently it is realised that the greatest problem arises from the complexity of the ingredients, whilst the actual process of mixing has one purpose only, namely the production of a uniform mix. Any means of improving the chances of obtaining a uniform mix will simplify the mixing process and should, thereby, increase the efficiency of mixing machines.

1.4 The effect of the Number of Ingredients on the Uniformity of Mixing.

The fewer the ingredients the better should be the chance of mixing them uniformly, because the interaction between different substances is reduced to a minimum. Unfortunately the trend in animal feeding at present is to increase the number of ingredients rather than decrease them, for example, mineral, vitamin and antibiotic supplements are commonly added to the basic cereal meals. The number of ingredients also varies with the type of animal to be fed and the purpose that the animal is to serve.

The ideal mixing process for feeding stuffs must be capable of handling variable numbers of ingredients whilst producing a uniform mix and where ingredients are present in comparatively small amounts it may be advisable to pre-mix them.

1.5 The effect of the Variety of Ingredients.

Cereal meals form the basic ingredients of feeding stuffs to which are added 'concentrates' to increase the protein content, pure chemicals, such as salt and minerals, and fibrous products to increase the bulkiness. From this very brief summary it can be seen that the type of particle in any feeding stuff will vary enormously, from powders to crushed whole grains. The heterogeneous composition of feeding stuffs will affect the efficiency of any mixing process designed to produce a uniform mix, therefore reducing the variety of ingredients should be beneficial.

1.6 The effect of Mix Quantity.

The quantity of materials to be mixed at one time depends on their bulkiness and this will have a direct effect on the mixer design. It is likely that the smaller the quantity to be mixed the better will be the chance of reaching uniformity in a given time.

The mix quantity will affect the size of sample to be used when testing for uniformity, this is referred to by some research workers as 'the scale of scrutiny.' If the sample is to represent the ration for one animal, then it is necessary for the correct amount only of each ingredient to be present in that sample. The criterion of uniformity would be the same irrespective of whether the ingredients were uniformly diffused throughout the mix or distributed in pockets.

It follows that the smaller the sample to be fed, or the greater the number of collective animals to be fed from one sample, the greater the need for a more intimate mixing.

1.7 The effect of Ingredient Proportions.

For similar materials one would expect the greatest uniformity to be achieved when the proportion of each ingredient was the same and uniformity would probably diminish as the proportion ratios increased. Experimentally this

was found to be untrue for dissimilar materials.

A completely uniform mix is one from which any sample taken will contain all the ingredients in their correct proportions.

1.8 The Effect of the Physical Properties of Ingredients.

The mixing process involves the movement of each ingredient so that its particles are uniformly distributed throughout the whole mass. This movement will depend upon the physical properties of the ingredients, particularly particle confirmation and moisture content, with, to a lesser extent of the effect of heat, electrical and chemical properties.

Nearly all ingredients of animal feeding stuffs are composed of solid particles, however, they differ in size, shape and density. Not only is there a difference between ingredients but between particles of the same ingredients too, for example a cereal grain when ground will produce fibre, protein and starch particles which differ in physical as well as chemical properties. The shape of a particle affects its movement, the greatest mixing ability should be achieved with ingredients whose particles are smooth and spherical shaped. The size of particles affects mixing too, small ones can pack into the spaces between large ones for example, whilst the different densities of particles will give rise to gravitational effects.

The moisture content of ingredients will affect the adhesion between contact surfaces of particles and so control the rate of dispersion. Adhesion and surface roughness are functions of friction which is a controlling factor with respect to the mechanical movement of particles and is considered more fully in the next section.

Heat effects are important in the mixing of liquids since they influence viscosity and produce convection currents, however, under conditions of normal atmospheric temperature and humidity, heat is not likely to affect the mixing of meals unless the actual mixing process itself generates heat. It is quite probable that each particle carries a minute electrical charge or will become charged from fields generated during mixing, in which case magnetic aggregation or dispersion may result. The value of this effect will depend on the amount of charge and the electrical conductivity of each ingredient which also depends to a large extent on its chemical composition.

1.9 The Effect of the Mechanical Properties of ingredients.

The forces employed in all mixing processes are either gravitational or centrifugal or a combination of both, hence particle mass is the most important physical factor. Once set in motion the particles will be influenced by these forces, but their movement will be complicated by collisions with one another and the mixing mechanisms. Particles in motion in an air medium behave similarly to liquid solutions, therefore their flow patterns can be determined approximately by the Froude and Reynolds formulae. Both formulae take into account particle size and initial velocity, the Froude Number associating them with gravity and the Reynolds Number with inertia and viscosity.

Viscosity is the resistance of a solution to fluid motion and is a function of the internal friction between molecules or, in the case of solid suspensions, particles. The rate of flow of particles will influence their mixing ability and hence the less viscous ingredients have a better chance of reaching uniformity in a given time. From this it can be seen that viscosity can be assessed quantitatively as a unit of time, the time being obtained for a measured quantity to flow through a small orifice, the apparatus for carrying out this test is called a Viscometer.

The friction between particle surfaces will determine also the angle of repose for a meal or mixture of meals. This is the angle made by the surface of the material to the horizontal when the material is poured freely on to a level table. The range will be from 0^{o} for a liquid to 90^{o} for a single solid object; particulate materials will form a conical heap with an angle of repose between these two values.

1.10 The effect of the Method of Mixing on the Uniformity of Mixing.

There are three basic methods of mixing feeding stuffs, one by hand and two by machine.

Originally all mixing was performed by hand using a shovel to turn the meals two or three times into conical heaps, it has been replaced largely by mixing machines or mixers as they are called. On farms batch mixers are common whilst the feeding stuffs manufacturers often use continuous mixers. The former process consists of a container and a mixing mechanism for a fixed quantity of

meals at one time and the latter employs a mechanical form for mixing the meals whilst they are in continual flow or conveyance.

The mixing mechanism must give the velocity to the particles which will cause them to intermingle until they are uniformly dispersed throughout the whole mix.

The method of mixing is relatively unimportant provided it is cabable of blending the ingredients completely.

1.11 The effect of the Rate of Mixing.

Mixing is a process which requires time to reach completion, the end being denoted by the required degree of uniformity. Therefore it is obvious that the mix will be least uniform at the beginning and will improve as the process continues, with some mixes complete uniformity may never be achieved, whilst some experiments with chemicals have shown that there may be a critical time after which uniformity decreases. The same trend will exist probably with the speed of the mixing mechanism, so that there may exist an optimum time of mixing and mixing speed for a particular design of mixer and mix.

1.12 The effect of the Mixer Design.

The design of a mixer must be based on all the previous considerations plus the fact that it must be reliable and practical. There are numerous mechanisms that can be used for mixing, the most common ones using rotary motion in association with the force of gravity. Basically a batch mixer consists of a container for the ingredients and an agitator to produce the diffusing motion. The shape of the container must be designed to suit the method of agitation and so prevent pockets of undisturbed material. Any sloping parts must be inclined sufficiently to prevent the material reposing on them and surfaces must have a low coefficient of friction to prevent retardation of flow. Flow is either streamline or turbulent, the merits of each in respect of uniform will need to be investigated.

The agitator need be no more complicated than a revolving paddle for mixing liquids, since the mere creation of hydraulic currents is sufficient to mix liquids or even suspensions in liquids. With solid particle "solutions" motion is

soon lost due to friction, the motion must be renewed continually by using gravity in the vertical plane or a moving conveyor in the horizontal plane.

The speed and size of the agitator is closely associated with the rate of mixing. It must avoid physical and mechanical deformation of the mix ingredients, such as heating or comminution.

Other design factors include, (1) power requirements which will vary with speed, capacity of the mixer and type of mixing mechanism; (2) the position of the entrance and exit of the meals; (3) the ability to empty the mixer completely and thus prevent contamination of a mix by ingredients from a previous mix; (4) the accuracy of weighing the ingredients in continuous mixers; and (5) the ability to repeat the mixing process accurately every time and so prevent any variations between mixes. These considerations show the design of a meal mixer to involve the careful study of the theory of mixing and the properties of the materials to be mixed, followed by extensive experimentation and testing.

SYNOPSIS OF THE STUDY.

1.13 The study commenced with a careful examination of previous work connected with the factors that affect the mixing of animal feeding stuffs and was reviewed in the second chapter under the heading "The Theory of Mixing". Then followed a study of the various designs of mixer which were used to mix solid particles, in order to record their advantages and disadvantages for future reference. From the foregoing investigations it was decided that an experimental mixer should be built to study the factors that affect mixing and to endeavour to inter-relate them as far as possible. The techniques employed in developing the experimental work were fully described under "The Experimental Procedure" and was followed by a classification and discussion of the results obtained.

It was impossible to study experimentally the results as fully as one would desire due to the considerable time involved in sampling and analysing each mix, however, sufficient data was obtained to provide an indication of the importance of each of the factors involved. This data should form a useful basis for further research into this complex, but fascinating, process.

2. A REVIEW OF THE MIXING PROCESS

2.1 Methods of Approach.

There appear to be two major approaches to the study of mixing, the first is the theoretical approach of investigating the behaviour of particles with known physical properties, and the second, or empirical investigation concerning the behaviour of heterogeneous particles as normally encountered in practice. To date work has only been done on the former aspect, initially with artificial mixtures and later with crystalline substances. The mixing of animal feeding stuffs must be formulated empirically because materials of dissimilar origins are used and their size reduction does not conform to any constant particle structure or pattern such as crystals. Therefore a careful investigation of the physical and mechanical properties of the materials used in animal feeding stuffs was necessary before studying their behavious during mixing. The object of the investigation then became an attempt to predict the "mixability" of known materials according to the principle of mixing employed.

PARTICLE SIZE CHARACTERISTICS.

2.2. The Particle sizes of materials used in animal feeding stuffs fall into the sieve range - 10^5 to $10^{1.5}$ microns. Since one micron equals 0.001 mm., this range covers particles that pass through a sieve opening of side 100 mm to those that pass through an opening of side 0.015 mm. In actual fact the upper limit rarely exceeds 15 mm.

To simplify the text all materials used in animal feeding stuffs will be referred to as "meals", i.e. "the edible part of any grain or pulse ground to a coarse powder and unsifted, or any ground or powdery substance resembling this" (Dictionary definition). Since most particles are irregular in shape, distinction must be made with respect to the meaning of particle size. The shape of a particle affects its size and weight, consequently sieving is only partially selective in sizing materials. Quoting Dalla Valle[1] "The characteristics and behaviour of small particles can be understood satisfactorily only when the methods of determining size-distribution are placed on a firm basis".

2.3 Equivalent Particle Shapes.

It is customary to reduce particles to equivalent spheres of equivalent

diameter, d_n.

Where $d_n = \left(\frac{6 \times \text{particles volume}}{\pi} \right)^{1/3}$

Since the volume of a sphere is $\frac{d^3}{6}$. It then follows that if there are N particles per unit weight and their density is p

$$d_n = \left(\frac{6}{\pi p N} \right)$$

In order to associate the shape of a particle to that of an equivalent sphere Wadell[2] described the Degree of Sphericity as the ratio of the surface area of the particle to the surface area of a sphere having the same volume. Similarly he developed the Degree of Circularity and found that to a close degree of approximation they were inter-changeable.

2.4 Mean Particle Diameters.

Instead of comparing particles by their equivalent diameters it may be advisable to use a form of the mean diameter each of which has its own special application as summarized below.

Arithmetic mean diameter, d_a is the average diameter of a group of particles, i.e. $d_a = \frac{\Sigma d}{N}$.

Geometric mean diameter, d_g is the mean of a group of particles whose size dispersion follows a geometric progression or the exponential law; it is given by taking the nth root of the product of the particle diameters

i.e. $d_g = \sqrt[N]{d_1 . d_2 . d_3 \ldots . d_N}$

Harmonic mean diameter d_h is the reciprocal of the average and would be used where the mean diameter of a group of particles involved another variable, such as time. It is expressed as $d_h = \frac{N}{\Sigma d^{-1}}$.

Median diameter, d_m is the diameter for which 50% of the particles are less than the stated size. It can be obtained by plotting the % less than stated size against the average size for the particle group, i.e. a size-frequency curve.

d_m is approximately the same as d_h, but $d_a > d_g > d_h$.

Statistical diameters take into account the ultimate size of measured particles when calculating their mean diameter. Unlike d_a, d_g, and d_m, statistical diameters take into account physical properties as shown below.

Length Mean Diameter $= \frac{\Sigma Nd^2}{\Sigma Nd} = d_l$

Volume Mean Diameter $= \left(\frac{\Sigma Nd^3}{\Sigma N}\right)^{1/3} = d_v$

Surface Mean Diameter $= \left(\frac{\Sigma Nd^2}{\Sigma N}\right)^{\frac{1}{2}} = d_s$

Volume - surface Mean Diameter $= \frac{\Sigma Nd^3}{\Sigma Nd^2} = d_{vs}$

Weight Mean Diameter $= \frac{\Sigma Nd^4}{\Sigma Nd^3} = d_w$

d_l is based on observed surface and disregards volume or total surface and as as an average is comparable to d_a and d_g.

d_v is based on average volume, i.e. the diameter whose corresponding volume divided into the total volume gives the total number of particles.

d_s is the diameter of a hypothetical particle having an average surface area, it is used in calculating the specific surface of a meal.

d_{vs} may be used if the total surface of a unit weight of material (e.g. specific surface) is desired.

d_w is the diameter of the particle of average weight in the group.

Note: d_l, d_v, d_s, d_{vs} and d_w are all larger than d_a.

2.5 Particle Thickness.

Microscopic examination of particles can only give details of observed surface areas, their thickness can only be approximate as it depends upon careful focussing. Errors may arise for small, thin particles and so far no satisfactory method has been developed to study them. Weigel [3] produced a hypothesis based on the assumption that the particles were split down from cubes and their average

thickness was expressed as a percentage of the observed diameter. This applies mainly to particles more or less uniform as to sphericity or to length, breadth and width.

SIEVING.

2.6 Particle size determinations can utilise either the geometric or gravitational characteristics of the particles or, in some methods a combination of both. The usual methods are dry or wet sieving, elutriation, sedementation or microscopic examination. Dry sieving lends itself more readily to the rapid size determination of meal particles and microscopic examination gives the most accurate shape determination, consequently these two methods were considered in order to develop methods for studying the size and shape characters of the meals used in the experimental work.

To obtain a range of sizes for a particulate sample it is necessary to use a nest of sieves having the required aperture sizes for the range to be studied. The fine wire mesh which forms the floor of a sieve provides a system of square apertures through which a particle may pass according to its minimum diameter in any of its three planes. The size of the aperture can be used to find only the mean particle size for the group of particles trapped by each sieve, consequently a definite size separation is not possible with sieves, but a much more accurate result can be obtained by calibrating the sieves according to different materials and conditions. The method of Hatch[4] involved the microscopic measurement of particles and determination of the median diameter by weight using the following relation which permitted the transference of size-distributions from a weight to a size basis.

$$\text{Log } d_{gs} = \log d_{gw} - 6.908 \log^2 s_{gw}$$

where d_g and s_g were statistical parameters for the geometric mean diameter and the deviation of the size-frequency curve respectively. The suffix 's' indicating size by count and the suffix 'w' size by weight.

2.7 Sieve Calibration.

Dalla Valle[5] gave an example of the application of the Hatch method of

measuring particles to the calibration of a nest of sieves and it is shown graphically in Fig.1. After sieving a sample material the particles were classified into size groups, the range in the example was between 100 and 1000 microns. The percentage less than the maximum size of each group was calculated and these values plotted against their respective sizes. In the case illustrated it was shown that 50% of the particles were less than 290 microns and 50% were greater, consequently, this was the mean diameter, d_m, of the sample; but it approximated to the size of a mesh 48 sieve instead of mesh 65. The reason for the anomaly was that the diagonal of a square mesh was greater than the length of its side; the side of a 65 mesh aperture was 210 microns and its diagonal 297 microns which was the same as the side of a 48 mesh aperture.

Calibration of sieve size

$$\log d_{gw} = \log d_{gs} + 6.098 \log^2 s_{gw}$$
$$= 2.462 + 6.098 (0.162^2)$$
$$= 2.478$$

where s_{gw} was 1.45 and log 290 = 2.462.

Therefore d_{gw} = 302 microns.

When applying the Hatch equations to a sieve analysis the summation curve should be plotted on a log-probability grid, should it result in a straight line then the equation applies. This method gave precise information on the mean particle size of a sieved material and samples obtained from the same source should give the same distribution, but samples from other sources will differ.

2.8 Particle size determination microscopically.

An empirical method of obtaining particle size was given by Heywood[6] and was based on the shape characters of particles shown in Fig.2. The following notation was used:-

T = thickness of the particle

A = side of square of the minimum sieve aperture in plan or elevation

L = length of particle, or distance between parallel lines tangential to the profile.

b = breadth of particle, or distance between parallel lines at right angles to the length.

Flakiness of particle, $h = \frac{b}{T}$

Elongation of particle, $n = \frac{L}{b}$

The mean projected diameter, d_p, of the horizontal profile of the particle was calculated as follows:-

$$d_p = \left(\frac{4}{\pi} 0.75\ bL\right)^{\frac{1}{2}}$$

$$= b(0.95n)^{\frac{1}{2}}$$

The value 0.75 was obtained experimentally for angular particles, whilst 0.77 was the equivalent value for rounded particles. Other particle characters were:-

Volume of particle = Cd_p^3

Surface of particle = fC^2

Where C = volume coefficient and f = surface coefficient, they could be found from values of h and n obtained experimentally and shown in Tables I and II in Appendix A.1. These coefficients were functions of a combination of the geometric shape and proportions of the particle, but changing the particle proportions without altering the geometric shape, until, b, L and T were all equal, gave the volume coefficient C_e, of this equi-dimensional particle which was a function of the geometric shape only, as shown by the equation:-

$$C_e = Chn^{\frac{1}{2}}$$

Hence the method existed for separating the effects of geometric shape and proportions of a particle and the C_e values in Table I were determined empirically.

TABLE I.

VOLUME COEFFICIENTS BY HEYWOOD[6]

Shape group	C_e
Angular - tetrahedral	0.38
Angular - primoidal	0.47
Sub-angular	0.51
Rounded	0.54

2.9 Specific Surface of Particles.

If the shape constants and the true meal density are the same, then the fraction of the total weight of the sample found in a certain size group must be the same proportion of the volume. Consequently the specific surface of the meal can be obtained from the surface mean diameter, d_a, which can be replaced by the composite projected diameter, d_p, to which it closely approximates.

$$\text{Specific Surface,} \quad S = \frac{f}{C_p} \cdot \frac{1}{d_p}$$

Since S is expressed as area divided by mass it gives a measure of the possible interfacial mixing between two meals. The shape of particles for any specific meal will be heterogeneous and hence will be more than one value of the constants f and C, therefore it will be important to classify each meal into shape groups. For example a cereal grain may be ground to give two basic types of particle, an elongated fibrous one and a rounded starchy one; the specific surface of each will vary considerably, but a general value for the meal as a whole could be obtained from the mean of their proportionate values.

$$S_{meal} = \frac{X_1 S_1 + X_2 S_2 + X_3 S_3 \ldots\ldots\ldots\ldots + X_N S_N}{100}$$

Where $S_1, S_2, S_3 \ldots\ldots S_N$ are specific surface values for different particle groups and $X_1, X_2, X_3 \ldots\ldots\ldots\ldots X_N$ are percentages by number of each present in the meal sample. The total specific surface of the meal would be

$$100S_{Meal} = \frac{X_1 f_1}{C_1 p_1 d_1} + \frac{X_2 f_2}{C_2 p_2 d_2} + \ldots\ldots\ldots\ldots \frac{X_N f_N}{C_N p_N d_N}$$

Other methods of determining surface area include absorption of gas, absorption of solutes from solution and heat of wetting. According to Gregg[7] only the former was capable of yielding values of surface area which were more than relative.

2.10 Methods of Sieving.

The efficiency of sieving depends upon the type of motion imparted to the nest of sieves. The object is to pass a maximum amount of material through a given sieve in the shortest period of time. The techniques used in sieving a sample have been standardised and should be followed if significant results are to be expected. The Keen[8] technique which is widely accepted in this country was adopted for the experimental work of this study. The repeatability of sieve results have been statistically analysed by Heywood[9].

Fahrenwald and Stockdale[10] carried out tests on five different methods of shaking sieves. These methods were listed in ascending order of efficiency.

1. Horizontal rotary motion by machine (37%)
2. Horizontal rotary motion accompanied by vertical tapping of the frame by a hammer 155 t.p.m. (43%)
3. Vertical jarring by striking the sieve bottom by hand (46%).
4. Horizontal jarring by tapping the side of the sieve by hand about 240 times per minute (53%)
5. High frequency vibration at 1400 vibrations per minute (57%)

Performance curves for sieve shakers were drawn by plotting the percentage passing each sieve against the amplitude or frequency of the vibrations. An example is shown in Fig.3 for the vibratory sieving method given above. In general it was found that the smaller the sieve aperture the shorter the amplitude and the more frequent the vibrations required.

$$\text{Efficiency} = \frac{\%\text{ of material actually passing}}{\text{Total \% of material capable of passing}}$$

Ross[11] suggested two methods of control for completeness of sieving.

(1) Sieving for a fixed time; this was most widely used and was perfectly satisfactory when the size range of the material being tested was not widely variable.

(2) Sieving until the amount of material passing the sieve in unit time less than a certain fraction of the amount of material on the sieve - e.g. to 10% of the sieve contents per minute. This was the sounder method, but was much more difficult to control.

The method used by Hepplethwaite and Hepherd[12] was fairly standard, but it is worth quoting as it is used for assessing the fineness of grinding meals. The size of sample was 100 grams and it was agitated in a nest of sieves for 5 minutes on a mechanical shaker which had a plain reciprocal motion with an amplitude of 0.05 in. and frequency of 1250 c.p.m. After shaking, the nest of sieves was dismantled and each sieve given two sharp taps to dislodge fine particles sticking to the underside. The material retained by each sieve was emptied on to a sheet of peper and weighed, and the sieve analysis calculated on a "percentage by weight" basis. Sieving was performed through 8-in B.S. sieves, each sieve had an aperture diameter equal to half that of the preceding sieve - namely $\frac{1}{8}$ in., 3/16 in., 7 mesh, 14 mesh, 25 mesh, 52 mesh, and 100 mesh.

2.11 Fineness Modulus.

The fineness modulus is a modification of the cumulative oversize method of representing sieve results and is defined as the sum of the weight fractions retained above each sieve divided by 100. It was devised by Abrams for concrete work and has been adopted by the A.S.A.E.[13] for determining the performance of feed grinders. The sieves used conformed to spec ification, A.S.T.M.E.11 of the U.S. Bureau of Standards, the mesh sizes being $\frac{1}{8}$ in., 4, 8, 16, 30, 50 and 100. A 1 lb. sample must be shaken for 5 minutes on a 'ro-tap' or similar machine and the weight of material on each of the 7 sieves and pan determined.

2.12 Sieve Analysis Example.

The method of obtaining the Fineness Modulus of a meal sample was shown by means of the sieve results given over:-

Sieve mesh	Aperture size microns	% material retained	Weight fraction
$\frac{3}{8}$ in	9520	1.0	x 7 = 7.0
4	4760	2.5	x 6 = 15.0
8	2380	7.0	x 5 = 35.0
16	1190	24.0	x 4 = 96.0
30	590	35.5	x 3 =106.5
50	297	22.5	x 2 = 45.0
100	149	7.5	x 1 = 7.0
Pan	-	0.0	x 0 = 0.0
		Total = 100.0	Total = 312.0

$$\text{Fineness Modulus, F.M.} = \frac{312}{100} = 3.12$$

If the percentage weight retained on each of the sieves is represented by w_1, w_2, w_3, w_4, w_5, w_6 and w_7 respectively the equation for Fineness Modulus is

$$\text{F.M.} = \frac{7w_1 + 6w_2 + 5w_3 + 4w_4 + 3w_5 + 2w_6 + w_7}{100}$$

2.13 Application of the Fineness Modulus.

The classification of ground grains into coarse, medium and find grades on the basis of Fineness Modulus by Silver[14] is given in TABLE 2.

TABLE 2.

Material	Whole Grain	Coarse Ground	Medium Ground	Fine Ground	Very fine Ground
Maize	6.00	4.80	3.60	2.40	1.80
Barley	5.00	4.10	3.20	2.30	1.50
Oats	4.50	3.70	2.90	2.10	1.40
Soya Beans	6.00	4.80	3.60	2.40	1.80
Wheat	5.00	4.10	3.20	2.30	1.50

The A.S.A.E.[13] also recommended a similar classification to the above as a supplement to the Fineness Modulus in order to indicate the relative uniformity of the different sizes of particles in a ground feed sample. The resultant uniformity Modulus consisted of three figures representing the coarse, medium and fine particles, the sum of which was always equal to ten.

This provided 66 different combinations for expressing the proportion

of each particle size group in a sample, ranging from 10 : 0 : 0 for a sample composed entirely of coarse particles, to 0 : 0 : 10 for a sample composed entirely of fine particles.

The test procedure was the same as that outlined in 2.11, the percentage weight of material remaining on the $\frac{3}{8}$-in., 4 and 8 mesh sieves was designated 'coarse', that on the 16 and 30 mesh sieves as 'medium' and that on the 50 and 100 mesh sieves and in the pan as 'fine'. In the example the percentages are 10.5, 59.5 and 30.0 respectively so that the uniformity modulus becomes 1 : 6 : 3 and it could be obtained by using the 8 and 30 mesh sieves only, provided that the Fineness Modulus was not required.

Strictly speaking the Uniformity Modulus is not a true measure of the uniformity of the ingredients in a mix because it takes into account only the distribution of the particle sizes. However, when coupled with the Fineness Modulus it does give a fair picture of the consistency of a sample. A modulus can be used only for relative comparisons since it has no dimensions, but the Fineness Modulus is a geometric mean of a set of minimum dimensions, namely the length of side of each sieve aperture. By plotting these lengths against Fineness Modulus a value for the mean length diameter d_l can be obtained for any known Fineness Modulus.

For the nest of sieves used in 2.11 and throughout the later experimental work in this study the basic equation is

$$d_l = 105\ (2)^{F.M.} \text{ microns}$$

where 105 is the mean diameter in microns for a zero Fineness Modulus, i.e. when all particles are in the pan.

During the study of meal particles the value of d_l, obtained by sieving, was compared with d_p, obtained by microscopic examination, along with their effects on the viscosity of meals.

PACKINGS.

2.14 Porosity of Packings.

Finely divided material packs according to the shape of the particles and

the void space between them. Theoretically the minimum void space is 26% whilst it is 48% for spheres. There is no method of describing a packing in terms of particle-orientation, it can only be described in terms of free space present, or the ease with which a liquid will flow through it. A small increase in compaction greatly affects the permeability of a packing.

$$\text{Voids, } V = 1 = \frac{\text{apparent density of meal } (p_a)}{\text{true density of meal } (p)}$$

$$= p_a \times \left(\frac{1}{p_a} - \frac{1}{p} \right)$$

Porosity, P = % of voids in the packing

$$= 100\ V$$

2.15 The number of particles in a packing.

The amount of solid material in a unit-volume is (1 - V) and it can be obtained by multiplying the mean volume by the number of particles.

$$\text{i.e. } 1 - V = G_v d^3 N$$

$$\text{Therefore } N = \frac{1 - V}{G_v d^3}$$

where N is the number of particles and G_v the volume shape factor, which will be $\frac{\pi}{6}$ for spheres.

It follows that the average volume occupied by a single particle is given by the equation -

$$\frac{1}{N} = \frac{G_v d}{1 - V}$$

If the particles can be counted then the value of V can be determined and used to find the diameter of an equivalent sphere, d_n. This was done by Furnas[15] when studying binary systems of spheres and was expressed as follows:-

$$d_n = \left(\frac{6}{\pi} \times \frac{1 - V}{N} \right)^{1/3} = 1.24 \left(\frac{1 - V}{N} \right)^{1/3}$$

When investigating systems composed of two particle sizes Furnas[15] found that the porosity of the packing was less for the mixture than for the individual components alone. This would be expected as the smaller particles would pack into the voids between the larger ones. The degree of saturation of the large

particles by the small ones depended upon the proportion of small particles and it was then shown that a condition of maximum density existed when the particles of each component had the same shape, specific gravity and voids.

2.16 Bulkiness.

In general the efficient use of packing space is increased by having mixtures of different-sized materials, but it is observed phenomenum that bulkiness increases with decrease in particle size. Bulkiness is the reciprocal of the apparent density

$$B = \frac{1}{p_a} = \frac{1}{(1 - V)\,p}$$

Both the apparent density and the bulkiness of meals will be affected by compaction such as tapping for example. Roller[16] investigated the relationship of particle size to bulkiness using four powders - anhydrite, gypsum, Portland cement and chrome yellow. Bulkiness was determined by tapping until no more material was required to fill varying sized containers to a predetermined level. Cylindrical containers were satisfactory providing that the ratio of the height of powder to the diameter of the cylinder was 6 or greater - this reduced the dispersive jogging effect of tapping.

The voids to particle size relationship was expressed in the form

$$V = k\left(\frac{1}{d}\right)^N$$

and it was found that there was a critical diameter for each powder with respect to this expression.

DYNAMICS OF SMALL PARTICLES.

2.17 Particles in Motion.

The flow of particles is the principle function in mixing ; it is affected by the forces of inertia, gravity and friction. All these forces have the same dimension, $\frac{M}{L^2t^2}$, but affect the flow in different ways; for instance a change in velocity will change the inertial and frictional forces but not the gravitational forces.

Expressions for these forces are as follows:-

$$\text{Inertia} = \frac{pv^2}{L}$$

$$\text{Friction} = \frac{uv}{L2}$$

$$\text{Gravity} = pg$$

p = density
v = velocity
u = coefft. of viscosity
L = linear dimensions
g = gravitational acceleration.

Establishing the ratios of these forces they then become dimensionless and characteristic of certain types of flow.

$$\frac{\text{Inertial forces}}{\text{Frictional forces}} = \frac{pv^2L^{-1}}{uv\,L^{-2}}$$

$$= \frac{pLv}{u}$$

$$= R \text{ - the Reynolds Number}$$

$$\frac{\text{Inertial forces}}{\text{Gravitational forces}} = \frac{pv^2L^{-1}}{pg}$$

$$= \frac{v^2}{L}$$

$$= F \text{ - the Froude Number}$$

R is important where inertia and viscosity are involved, as in the case of particles in motion, whilst F must be taken into account when gravity helps to determine the flow pattern.

2.18 The Motion of Particles in a Fluid.

The mixing of meals involves the motion of particles in an air medium, the resistance of this medium to flow will be proportional to the density and velocity of the particles and the viscosity of the air. This is the basis of Stokes' Law for particles moving in a streamline motion. However, if the resistance to flow also varies with the density of the air rather than its viscosity this can be equated to give Newton's Law for particles moving in a turbulent motion. In practice there is no clear demaraction between streamline and turbulent flow, so that a zone must exist between them where the resistance

to flow is a function of both density and viscosity.

The flow patterns will be complicated still further by the direction of the initial velocity of the particles and when it is considered that most mixing mechanisms impart more than one directional force on the particles the task of predicting flow patterns for the mixing of meals is beyond the scope of this work. However, it is worthwhile recording that Lapple and Shepherd[17] developed equations for horizontal, vertical and centrifugal motion of particles in the streamline and turbulent flow zones.

For Horizontal Motion.

$$\frac{dv}{dt} = \frac{p_o C_r a v^2}{2m}$$

For Vertical Motion

$$\frac{dv}{dt} = \frac{g(p-p_o)}{p} - \frac{p_o C_r a v^2}{2m}$$

For Centrifugal Motion.

$$v_c = \frac{d^2}{C} \cdot \frac{p-p_o}{m} \cdot rW$$

Where:

C_r = Coefficient of resistance of the medium

P_o = Density of the medium

a = Particle cross-sectional area

m = Particle mass

p = Density of the particle

v_c = Centrifugal settling velocity

r = Radius of circular path

W = Angular velocity of particle (radians).

These equations could not be solved explicitly, but could be determined approximately by integration for small increments in time. In the case of the centrifuge it was assumed that the velocities of the particle and the medium were the same.

2.19 The Motion of Meal Particles.

In the case of meals each particle is influenced by its neighbour and hence its projected path will not conform to that followed in free motion. Its velocity will vary similarly and continuously in a mixture of heterogeneous particles, consequently, meals can be regarded as fluids when they are being mixed in bulk. The legitimacy of this assumption would be investigated with special reference to the affect of flow characteristics on the intermixing ability of different meals.

The analogy between meals and fluids has one major flaw which arises from the fact that the smallest mobile unit is not molecular, but is considerably larger. Due to these larger units the interfacial friction between them often becomes a limiting factor to movement, this is commonly known as "bridging" with meals. The greater the degree of packing then the greater the reaction between particles with a subsequent increase in the force of friction, which is dependant upon the coefficient of friction between the surfaces in contact and the resultant force between the surfaces.

The greater the degree of packing of particles then the nearer the meal approaches to a solid body rather than a fluid. Thus the fluid properties of meals can be accepted only in the range of flow values when there is sufficient interstitial air to prevent flow retardation. When there is an excess of air the particles will behave like a suspension in a fluid medium.

Since viscosity is the measure of friction in fluids there should be a direct relationship between it and the interstitial air or voids.

$$V \propto \frac{1}{u}$$

therefore

$$V = p_a \left(\frac{1}{p_a} - \frac{1}{p} \right)$$

$$= \frac{k}{u}$$

2.20 The Viscosity of Meals.

When the apparent density, p_a, of a material equals the particle density, p,

then the material is a solid and its voids are zero. The maximum value of viscosity then becomes infinite so that the term $\frac{k}{u}$ also approaches zero, porosity is also zero. But when the apparent density is the same as the fluid density, i.e. $p_a = p_o$ then the voids are at a maximum, V = 1 and porosity is 100%.

From this it can be supposed that the larger the particles the less viscous is the meal and the easier it will flow. The lighter the particles the greater the retarding effect of the medium and the inter-reaction between particles, whilst the supposition can be made that the greatest rate of flow will be for meals composed of large dense particles.

Since $v \propto d_p$, then inse ting a constant, $v = kd_p$.

The rate of flow of meals could be measured in a viscometer in the same way as other fluids; if a constant volume of meal is allowed to flow through an orifice from a container then the time for complete discharge should bear a direct relationship to the kinematic viscosity, u_k. This statement was based on the reasoning of Lewitt[18] who showed that the rate of flow depended on a non-dimensional coefficient once the dimensional factors had been eliminated by keeping them constant. Consequently this coefficient, $\frac{puk}{u}$, provided a means of comparing viscosities of two or more fluids. The time of discharge was shown to be proportional to the reciprocal of the kinematic viscosity of each fluid and hence the insertion of a constant the following equation was produced,

$$t = \frac{c}{u_k}, \quad \text{or} \quad tu_k = \text{constant}$$

Any type of viscometer based on this conception cannot give a direct measurement of viscosity, but it can be obtained by comparing the times for different meals with the times of discharge for liquids of known viscosity in the same viscometer. In this way the viscometer can be calibrated and used to obtain reasonably accurate values of kinematic viscosity as was shown in the experimental work section of this study.

2.21 Mechanics of Mixing.

It is difficult to treat the mechanics of mixing non-Newtonian liquids, plastics and solids theoretically, but according to Danckwerts[19] progress was likely to depend on planned experiments regulated by physical insight and the use of dimensional analysis.

A theory of the absolute energetic efficiencies of mixing processes is required in order to discover how much of the energy supplied to a mixer is essential and how much is dissipated fruitlessly. The quicker the operation is performed the greater is the energy expended, consequently mixing becomes a compromise between time and energy in relation to the uniformity of the mix. The actual mixing mechanism should provide a continuous motion to the particles so that the ingredients can be dispersed and diffused amongst one another. There are three forms of motion available for this purpose:
(1) Horizontal straight-line motion, (2) vertical straight-line motion, and (3) radial centrifugal motion. (cf. section 2.18). It is usual for a mixer to utilise a combination of these forms of motion in order to increase the rate of mixing.

Hand mixing into conical heaps makes use of the downward vertical force of gravity but the particles are deflected sideways due to the stationary mass of the heap onto which they fall, therefore the final motion is downwards at an angle, Y to the horizontal. Y is the angle of repose for the materials being mixed. Mixing is brought about by spreading successive layers of meal over the surface of the cone until the whole batch has been heaped together. The process is repeated until such time as the ingredients are judged to be uniformly mixed.

Mechanical mixers operate in a similar fashion, but normally they combine either a horizontal or a vertical motion with centrifugal motion. For example, the common auger-type of mixer continuously conveys the meals through the centre of the batch from one end to the other and rotating them as they travel. In the case of the vertical auger mixer there is a complete cycle as follows; meals enter the auger at the base of the hopper and are conveyed upwards by the auger to be dispersed radially at the top, then they settle by gravity as other

meals are removed from the bottom until they return to the bottom again themselves. This cycle is repeated in a batch mixer until the batch is uniformly mixed. In a continuous mixer the ingredients are fed continuously into the mixing mechanism which conveys them in a horizontal or vertical direction until they are uniformly mixed when they are automatically discharged. The length of the mixing mechanism is determined by its flow rate and its ability to produce a uniform mix.

The various types of mechanism suitable for mixing animal feeding stuffs are discussed more fully in the next chapter which is entitled "Meal Mixers."

THE UNIFORMITY OF MIXING.

2.22 Standards of mixing efficiency.

The efficiency of mixing can be defined as the ability of a mixing process to produce a uniformly consistent sample from a number of different ingredients. It follows, therefore, that it is impossible to define any degree of efficiency without being able to measure the uniformity of the product. Uniformity is a function of time, the composition of the mix and the method of mixing, consequently these three factors must be used to determine the efficiency of a mixing process in conjunction with the uniformity of the product.

In the course of this study it was proposed to investigate the efficiency of different mixing mechanisms by comparing them. The comparison could be be made, either at various times when using a standard mix composition, or at a standard time when using a range of mix compositions. In either case the criterion of mixing ability would be the degree of uniformity of the mix, consequently, a procedure had to be developed for testing the degree of uniformity.

2.23 Factors affecting the testing of uniformity.

The uniformity of a product must be obtained by taking a sample and testing it, the degree of accuracy would depend upon the size of this sample and the test procedure. Considering the size of sample first; when scrutinising a mixture regions of segregation become apparent, the size of these segregations to be

tolerated will vary with the requirements of the mixture and the amount to be fed to an individual animal. The term "scale of scrutiny" is applied to the maximum size of these regions of segregation that will cause it to be regarded as imperfectly mixed. It can be defined only imprecisely as an order of magnitude, such as weight or volume in the case of meals; for example, a feeding stuff would be sufficiently mixed if a sample corresponding to a single ration taken from anywhere in a batch contained all the ingredients in their correct proportions or within certain close limits. It follows that the scale of scrutiny for testing the uniformity of a feeding stuff must be a quantity considerably less than the quantity of a single ration.

The segregation of mixtures can be studied most easily when the particles are large since it is possible to decide by observing the variation between samples whether the positions of the different particles have been randomised or not. Initial work by Lacey[20] with relatively large spheres (0.2 in diameter) indicated that uniformity could be expressed by a line on a suitable graph which would provide both quantitative and qualitative methods of comparing mixtures and the performance of mixers. The statistical procedure employed by Lacey to test uniformity was based on the variation in composition amongst samples that were taken at any time from certain types of mixture. The standard deviation, s, between the observed and required quantities of each ingredient in a sample was used and then the variance (s^2) for a completely randomised mixture of uniform particles become :

$$s_r^2 = x\frac{(1-x)}{N}$$

where s_r was the standard deviation between samples of a completely randomised mixture, x was the overall proportion of one ingredient and N was the number of particles in each sample. In a completely unrandomised system, the variance, s_o^2, was independant of the number of particles.

$$s_o^2 = x(1-x)$$

When a material was partially mixed the degree of mixing could be

represented by a modulus, M , that was suitable for expressing the dispersion of one ingredient only in a mixture, several values would be obtained for a mixture of more than two components. If s was obtained from examination of a large number of samples, $M = \frac{s_r}{s}$.

Kramers and Knoll[21] used the alternative expression, $M = \frac{s_o - s}{s_o - s_r}$

which was useful in that M was zero for an unmixed material and unity for a completely randomised one ($s = s_r$). Using variance instead of standard deviation the expression became:

$$M = \frac{s_o^2 - s^2}{s_o^2 - s_r^2}$$

M could be replaced by (1-M) in order to give a value between zero and unity for the degree of uniformity.

In the case of fine particle mixtures the scale of scrutiny can be reduced and still embrace a large number of particles of each component and when it is fully randomised it will be uniform in composition for all practical purposes. Buslik[22] studied mixtures of particles which had sizes varying over a wide range and found that the fine particles tended to segregate in the voids between the large ones. Danckwerts[23] considered the problem of defining and measuring the goodness of mixing fine particles and explained that in a fully randomised mixture the composition could be said to be the same at all points, a point being a region much smaller than the scale of scrutiny, but larger than the ultimate particles. In an imperfectly mixed batch the composition could vary smoothly and continuously from point to point. Two distinct quantities were required to describe the condition of an imperfect mixture with any precision, these were called the "scale of segregation" and the "intensity of segregation."

(1) Scale of segregation was the linear or volumetric measurement of the size of the regions of segregation since the regions were usually irregular in shape and of diffuse outline a special statistical method had to be used to define and determine their scale. This was based on the degree of correlation between

the compositions at neighbouring points and was similar to that used in the statistical theory of turbulence. A similar method was used by Blumberg and Maritz[24] and is fully described in section 2.25.

(2) Intensity of segregation was a measure of the departure of the composition from the mean value and averaged over all points in the mixture. The intensity was independent of the size of the regions of segregation, but depended upon the dilution of any one ingredient by the others. Consequently the degree of dilution was a measure of the uniformity of the mix and the greater the divergence from the completely diluted (or uniformly mixed) state the greater the degree of "unmixedness". The term "unmixedness" was defined by Hawthorne[25] and used to measure the intensity of segregation in air/fuel ratios for internal combustion engines.

2.24 Determination of Uniformity Standards.

The criterion of uniformity of mixing may be sometimes the scale of segregation and sometimes the intensity of segregation, but more frequently a combination of the two. If the scale is very large then samples of the mix drawn for use from different parts will not match, however, if the intensity is sufficiently low the discrepancy will become negligible. It is desired that a series of samples of a given size should display not more than a specified variation in composition and it is the product of the scale and intensity of segregation that must be reduced to a certain value by mixing. The former is a statistical determination based on sampling and the latter is a kinetic determination based on the mixing process.

Brown[26] considered the ultimate objective in determining a standard of uniformity to be the arrival at a practical criterion sufficiently simple for application to full-scale plant and based on the use to which the mix was put. Supposing this determined a minimum volume within which segregation was relatively unimportant and the variance between a series of these volumes was small, then the relationship between the minimum volume and the total volume provided a criterion of mixing.

The foregoing evidence supports the hypothesis that the degree of uniformity depends upon the deviation from the desired constituency by any sample of a certain maximum size, and that the standard for the uniformity of mixing should

have a statistical basis. From the theory of probability it can be shown that, if a number of samples are taken and their errors are purely accidental, the most probable value of the quantity sought is such that the sum of the squares of the deviations of individual samples from the expected is a minimum. This is known as the 'Theory of least squares' and from it the 'standard deviation' or 'root mean squares' is derived as follows:-

$$\text{Mean deviation} = \frac{\Sigma(x-\bar{x})}{N}$$

$$\text{Variance, } s^2 = \frac{\Sigma(x-\bar{x})^2}{N}$$

$$\text{Standard deviation, } s = \sqrt{\frac{(x-\bar{x})^2}{N}}$$

Where N is the number of samples, x the proportion of a component in a sample and $\bar{x}$ the mean proportion of that component.

Michaels and Puzinaukas[27] developed this further to provide a satisfactory standard of uniformity and used it to test the mixing of chemicals in a muller-type mixer. Neither 'standard deviation' or 'standard error' allow for variation in the value of the mean, in this instance the latter precludes the testing of single samples as it embodies 'degrees of freedom', i.e. $(n-1)/n$ instead of n. However, the coefficient of variation as defined by Brown[28] provided a measure of the goodness of fit by dividing the standard deviation by the mean.

$$U_c = \text{coefficient of variation} = \left(\frac{\Sigma(x-\bar{x})^2}{N\bar{x}^2} \right)^{\frac{1}{2}}$$

Uc approaches zero as the batch is better mixed but the initial value for an unmixed batch varies with the composition, to overcome this Michaels and Puzinaukas[27] showed that the uniformity of an unmixed batch U_o, could be determined as follows -

$$U_o = \frac{(1-\bar{x})^{\frac{1}{2}}}{\bar{x}}$$

and from this they developed the Uniformity Index, U, as the ratio of the mixed

and unmixed batched.

$$U = \frac{U_c}{U_o} = \left(\frac{\Sigma (x - \bar{x})^2}{N\bar{x}(1 - \bar{x})} \right)^{\frac{1}{2}}$$

This index varies from unity for a completely unmixed batch to zero for a uniform one but as x refers to the proportion of an individual component, there is a different index for each component in a non-uniform batch. The expression of uniformity as an index for mixtures containing several components is difficult to achieve, although it must be based on all the component Uniformity Indices. Any mean Uniformity Index does not account for the values of the least or most uniformly distributed components and the summation of the Uniformity Indices of all components will have a variable maximum value depending upon the number of components in the mixture. The only satisfactory alternative is to use the standard deviation of the Uniformity Indices which the writer uses to obtain an over-all Uniformity Index, U_z, for any mixture as a whole.

$$U_z = \left(\frac{\Sigma U^2}{N} \right)^{\frac{1}{2}}$$

Once again this index varies from unity for a completely unmixed batch to zero when all the components are uniformly distributed throughout the batch.

SUMMARY OF PREVIOUS EXPERIMENTAL WORK ON MIXING.

2.25 Blumberg and Maritz[24] used a statistical method of assessing uniformity based on random sampling throughout the batch. The completely mixed state obtained when the probability of drawing an ingredient A at a certain point was the same at all points in the mixer; i.e. for a completely mixed batch the values $x_1 \ldots\ldots\ldots\ldots\ldots\ldots x_N$ obtained by random sampling could be regarded as N independent statistical variables each with the same normal distribution. x was the ratio of the number of particles of A in the sample to the total number of particles in the sample.

Using a batch composed of half red and half blue sand and mixing in an inclined rotary drum until uniform, the assumption above was proved to be acceptable according to the Chi-square test. In the same way mixing would be

incomplete if the probability of drawing A were not identical at all points in the mixer.

The mix was considered as either completely or incompletely mixed depending on whether the statistical hypothesis, H_o, for the mean variance between samples could be accepted or rejected. Fundamental importance was attached to the approach of a mixture towards the completely mixed state rather than the degree of mixing. As a means of determining this $\emptyset$ was used - a Chi-square variable.

$$\emptyset = \bar{x} \sum_{i=1}^{N} (x_i - s_o)^2$$

Where:

$\bar{x}$ = expected mean value.

x_i = ratio for incompletely mixed sample.

s_o = transform of the total proportion of A in the batch.

A critical level of O.OI for H_o was chosen according to the Chi-square tables for probability distribution.

Further experiments were carried out to obtain the time before the mixture of red and blue sand became complete. An important feature concerned the number of samples, in each case the hypothesis was tested with comparatively few (about IO) and large (about 8O) numbers of samples, and it was found that the acceptance of rejection of H_o was independent of these sample sizes.

2.26 Coulson and Maitra[29] carried out a kinetic line of approach based on the interfacial surface between two solids. Mixing was performed by causing the diffusion of two ingredients across the boundary between them and so increasing the area of interface which was used as a measure of the degree of mixing. Fick's Law of diffusion was modified in terms of the interfacial area of surface per unit volume of mix, S.

$$S = S_o (1 - e^{-kt})$$

Where

S_o = max.surface per unit vol.for the given system.

t = time to achieve S.

As it was not possible to measure S it had to be correlated with some

observable property of the system, in other words if a sample contained both ingredients it also contained part of the boundary surface. The surface S was divided into N small elements, ℓ, so that

$$N = \frac{S}{\ell} = N_o (1 - e^{-kt})$$

For complete mixing every volume element had a small surface element, ℓ, and so corresponded to a maximum number of small elements, N_o, and the maximum number of volume elements corresponding to N_o.

$$\text{i.e. } N_o = \frac{V}{v} = \frac{\text{Total mix volume}}{\text{Sample volume}}$$

At any instant the fraction of the system mixed was $\frac{Nv}{V}$ and unmixed was $\frac{N_o v}{V} - \frac{Nv}{V}$

Setting X = percentage unmixed

$$\frac{X}{100} = \frac{N_o v}{V} - \frac{Nv}{V}$$

$$= \frac{N_o v}{V} \left[1 - (1 - e^{-kt})\right]$$

$$= 1 - (1 - e^{-kt}) \text{ since } N_o v = V$$

Giving the rate of mixing as

$$t = \frac{1}{k} \ln \frac{X}{100}$$

which could be related to surface, S, and used as measure of the degree of mixing after any time, t, because

$$\frac{S}{S} = 1 - e^{kt} = \frac{1 - X}{100}$$

Therefore

$$t = \frac{1}{k} \ln \frac{S_o}{S_o - S}$$

Experiments were then carried out to examine the rate of mixing equation under a number of different conditions for mixing two solids in an inclined

drum mixer. The rate of mixing was influenced by the angle of drum inclination, speed of drum rotation, drum volume, particle size and other physical properties of the materials. It was also found that k varied almost linearly with the following:-

(a) particle size,
(b) relative volume of the two materials,
(c) particle size-ratio.

The functions of speed and angle of inclination were complex, in the former case a peak value for k was obtained when the whole mass rotated with the drum and in the latter case the maximum value of k corresponded to the maximum free surface area.

Mixing coal and lead nitrate showed that an intimate mixture could be unstable, separation occurred after a critical time but a partly mixed system could then become stable. When mixing coal and salt of different sized particles the stable condition was one of complete separation with the coarse particles at the top. Equilibrium mixing was observed in two cases:-

(1) Particles of similar size, but widely different density,
(2) Particles of similar density, but different size.

There was considerable difficulty in mixing materials of widely differing proportions, the wider the proportion the longer the time to reach uniformity. Finally experiments showed that more rapid mixing was affected if the two materials were fed simultaneously into the mixer rather than one after the other.

The one criticism of this work is that the degree of mixing was not based on statistical standards, it was simply stated that if N samples out of the 30 taken each time had the same composition as the whole system, then the mixture was $\frac{N}{30}$ x 100% mixed. This equation appears to have been used also by Hixson and Tenney[30].

2.27 Brothman et al.[31] also used the kinetic approach starting with the hypothesis $\frac{ds}{dt} = k(S_o - S)$ an equation for the rate of mixing was obtained in the form:

$$\text{In } \frac{100}{X} = g.S_o(1-e^{-kt})$$

where g is a constant.

The interfacial surface was divided into a fixed number of elements and as mixing proceeded the element size increased but their number remained constant, but no experimental work was performed to substantiate this theory.

2.28 Kramers and Knoll[21] expressed the efficiency of mixing in stirred tanks in terms of the product of the rotational speed of the agitator and the time for sufficient mixing. If this product was called Q , then

$$Q = \frac{vt}{60}$$

v = agitator speed, r.p.m.

t = sufficient mixing time, sec.

The flow region used was $45{,}000 < R < 200{,}000$

$$R = \text{Reynolds No.} = \frac{vL^2}{60u_k}$$

d = agitator diameter, in.

u_k = kinematic viscosity, in^2 per sec.

$$F = \text{Froude No.} = \frac{g}{d(v/60)^2}$$

Q was constant since turbulence was fully developed about R = 100,000.

If meals can be considered to behave as liquids then this equation for mixing efficiency should also hold good over the same flow region.

2.29 Kirkham[32] tested the uniformity of quality of mixing concrete by emptying the whole batch from the mixer into eight compartments and then samples were drawn from each. The water/cement, sand/cement and gravel/cement ratios were calculated and the standard deviation of each determined. This method was preferred to that in which the variation was given for each constituent in the 8 samples because it emphasized the important variations in making concrete.

Plotting mixing time against the several ratios he produced curves that indicated:-

(i) the maximum uniformity possible.
(ii) the minimum time to that degree of uniformity.

The combination gave the minimum mixing time when the standard deviation was constant.

These tests were repeated with mixes of ingredients in different proportions

and it was found that differences in mixing time for uniformity were almost non-existant, although the standard deviation varied with the different mixes which indicated variations in quality.

2.30 Lowry[33] when producing amatol for explosives used the statistical method outlined by Herdan[34], which considered that the most 'completely' randomised mix occurred when the standard deviation was minimum. The mixing of 80% ammonium nitrate and 20% T.N.T. was tested after certain periods of time and the standard deviation of the nitrate from 80% calculated. The mean deviation was obtained for each group and mixing was assumed complete when it was a minimum constant.

$$Q = \frac{s_t}{s_T}$$

s_t = observed standard deviation at time t

s_T = minimum constant standard deviation at time T.

The variations in s_T and T that occurred due to random sampling could have been overcome by using the Quality Control Chart technique of Herdan 35.

3. A REVIEW OF MIXER DESIGNS.

3.1 Meal Mixer Definition.

A mechanism designed for mixing of animal feeding stuffs is termed here a meal mixer. The various designs of mixing mechanism that have been employed, or could be employed, for this purpose are discussed and compared in this chapter on a purely practical basis.

Meal Mixers must consist of two basic parts, a container for the meals to be mixed and a mechanism to impart motion to the meal particles in such a way that they are mixed together as uniformly as possible. Since the mixing mechanism is the essential feature the design of the container depends largely upon the capacity of the mixer; each type of meal mixer was reviewed as a complete unit.

3.2 Methods of mixing meals.

There are three methods of performing the function of meal mixing; They all depend upon the motion of the meal particles during mixing and can be designated as follows:-

(1) Convective mixing
(2) Diffusive mixing
(3) Shear mixing.

Any type of meal mixer can employ these methods separately or in combination.

Convective Mixing is the progressive movement of particles from one position to another and an example of its use is the trough type mixer with a rotating auger producing the movement. Each component of the mix will follow the flow pattern until it is completely intermingled with the others, consequently the degree of mixing will depend upon time but should be independant of sample size provided the sample is small.

Diffusive Mixing involves the distribution of particles over a freshly developed interface as in a rotary drum type mixer. The interface or boundary surface between the components is a minimum at the start and as mixing continues it increases to reach a maximum when dispersion is complete. Like convective

mixing the degree of randomisation varies with time and is independant of sample size for small samples.

Shear Mixing is produced by the formation of slipping or shear planes in a process similar to the shuffling of a pack of playing cards. A convergence-divergence type of mixer provides an example of shear mixing. The interfacial surface is increased by the continual cutting off of layers from the batch and merging them together so that the constituents of each layer become progressively more randomised by a process that is dependant on both time and sample size for the assessment of the degree of randomisation.

Little research work has been published concerning the design of meal mixers, therefore it is proposed to limit this chapter to a discourse on the different types of mixer, their practical use and any relevant experimental observations.

TYPES OF MIXER.

3.3 Vertical Auger Mixers.

This type consists of an upright chamber and mixing auger and is generally used for mixing batches of feeding stuffs. According to Simmons[36] vertical batch mixers as a class must nearly meet the requirements of the compound miller for dry materials; they are cheaper and take less power than other types and, if fitted with quick feeding and delivery facilities, are capable of mixing a batch of ingredients in 15 - 20 minutes sufficiencly well for most compound purposes. A trial carried out at the N.I.A.E. by Hebblethwaite[37] suggested that 15 minutes mixing in a vertical machine was insignificantly different from thrice-turned hand mixing or 3 minute mixing in a horizontal machine and that the results obtained called into question the often quoted statement that horizontal mixers were more 'efficient' than vertical mixers. It seemed likely that horizontal mixers could achieve a good mix in less time than vertical mixers, but, when both types were allowed full time, the final result appeared to be no better.

3.4 Design Features of Vertical Mixers.

The basic design consists of a vertical, cylindrical chamber with an

inverted-cone hoppered bottom and a spiral auger running up the centre as shown in Fig.4. The principle of operation involves carrying meal from the hopper to the top of the chamber by the auger to be discharged radially and fall by gravitational force to the hopper again. This process is like a continuous fountain or cascade and combines convective mixing by the auger with diffusive mixing in the flow down the chamber.

The various designs of this type of mixer are described most satisfactorily under the heading of each design feature that can be incorporated.

Feed Inlet: the position of the feeding-in point alters the foundational design of the mixer, it can either be fed from the top or the bottom.

(1) Top Feed is shown in Fig.4, the inlet consisting of a hinged lid, the meals filling the chamber ready for pick-up by the auger. The mixer is usually positioned between floors, so that filling is performed on the floor above and emptying on the floor below.

(2) Bottom Feed is shown in Fig.5, the auger is continued downwards so that the feeding-in point is either below or at ground level. This design is suitable for single storey buildings.

Discharge Outlet; the discharge is nearly always at the base of the hopper at which point vanes are often fitted to the auger to assist discharge and to minimise the possibility of unmixed meal clinging to the sides of the mixer. An alternate method of discharge is to use the auger as an elevator to discharge the meal from the top of the mixer to any desired position. (Fig. 6).

Mixing Auger: the pitch of the auger blades should be gradual enough to give a good throw to the material and keep it circulating, thereby minimising the tunneling action through the batch. A method of overcoming tunnelling, which also reduces the starting torque is to fit a cylindrical shroud around the auger, except for the part at the bottom of the hopper, of course. It is possible that the shroud worsens the mixing rate, but some manufacturers claim improved uniformity of output by fitting conical skirts to the shroud, or making apertures in the shroud so that a proportion of the elevated material is discharged through

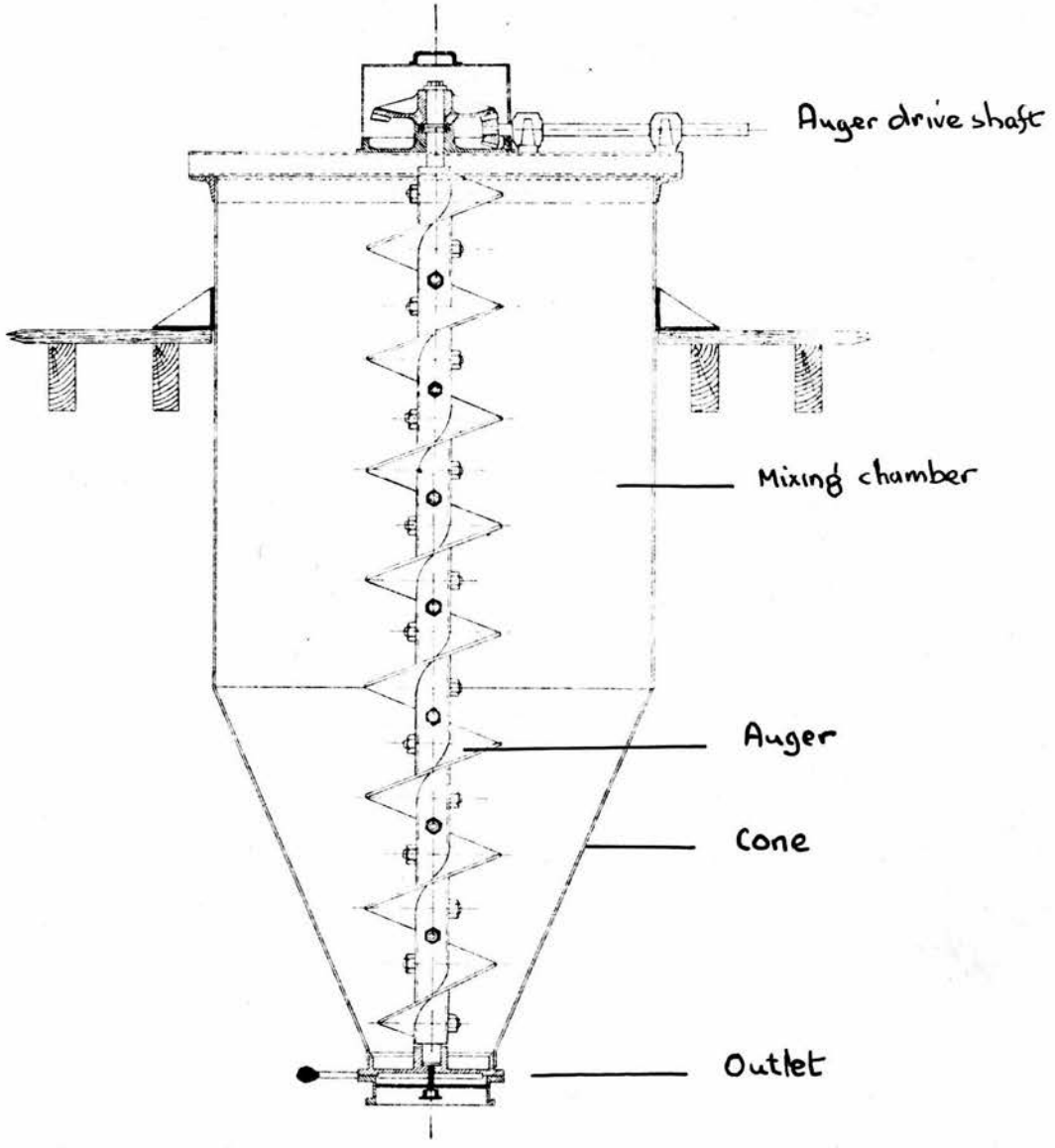


FIG.4 CONICAL MIXER

FIG.5 **Bottom feed vertical mixer with side elevating auger**

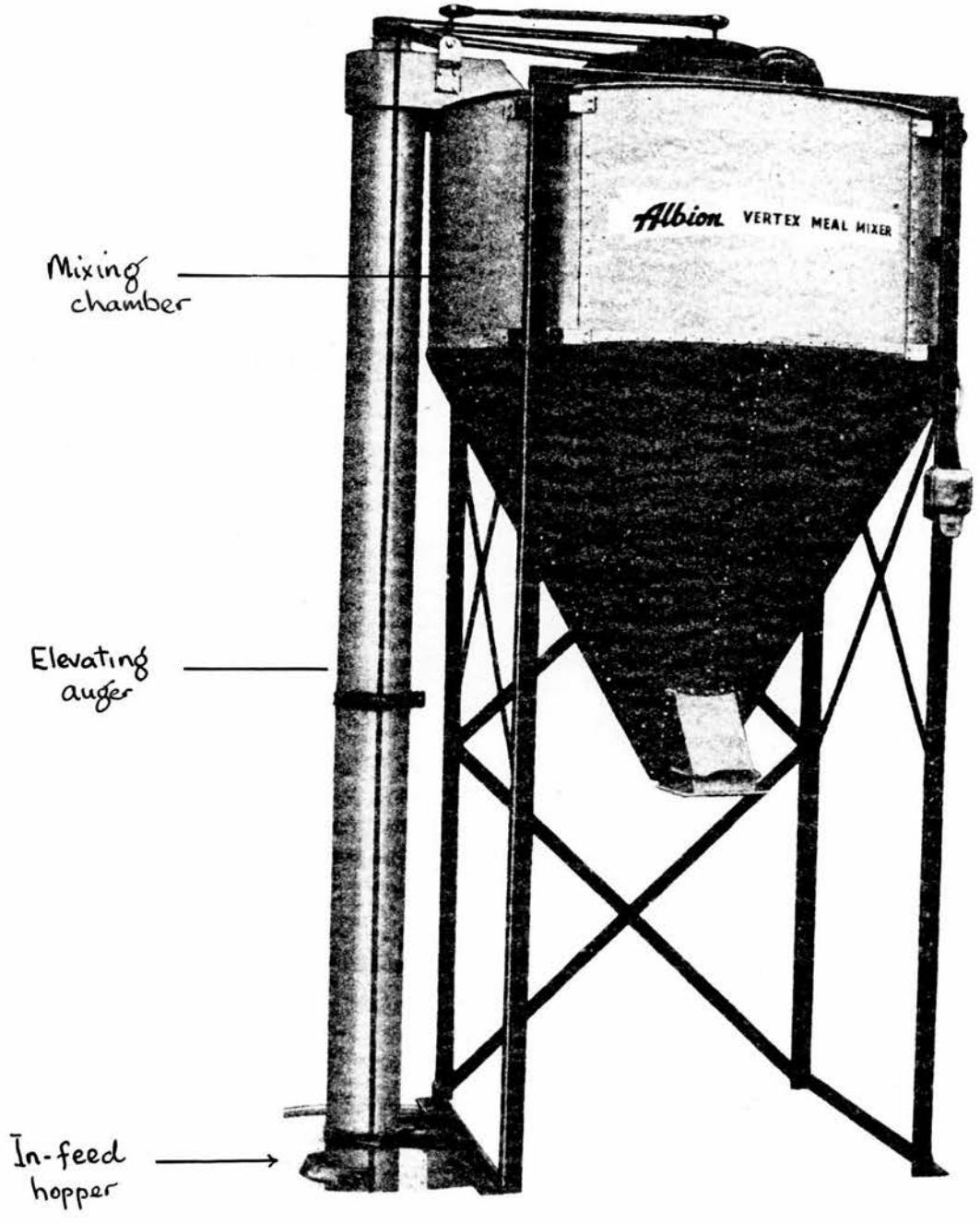


FIG.6 Vertical mixer with top discharge.

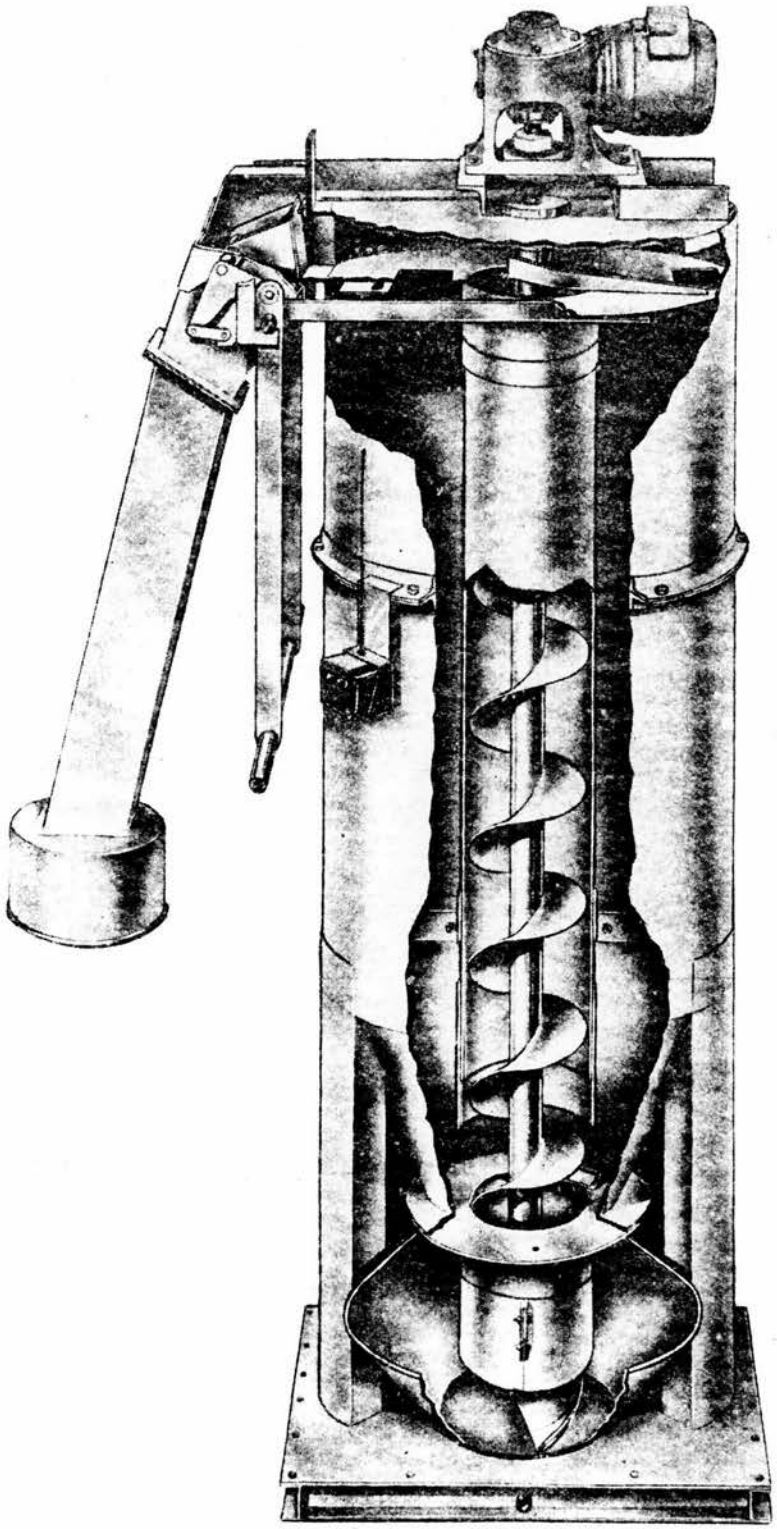


Fig. 7
Vertical auger mixer

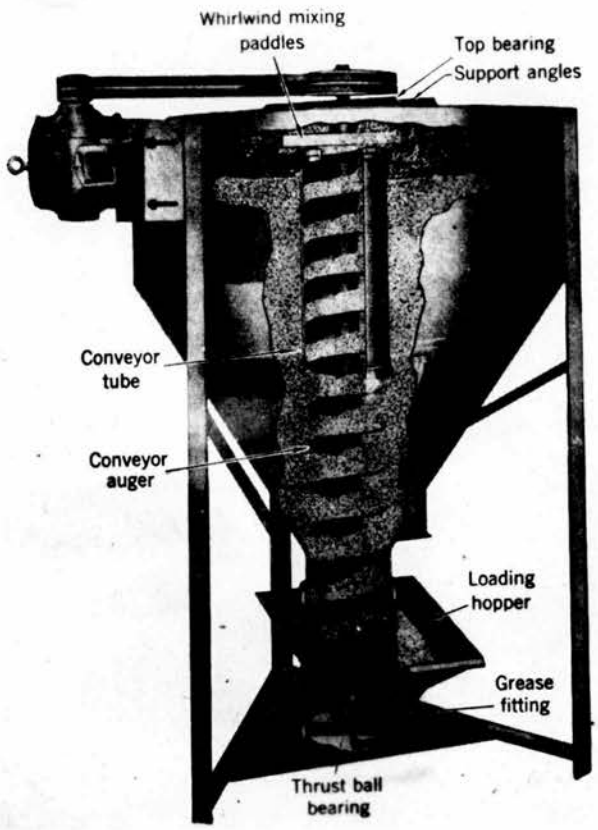


FIG. 8 —The Nauta counter-current mixer.

the apertures at various heights. Alternative to fitting a shroud the spiral-shaped auger can be tapered from top to bottom. The auger may be plain or notched and in either case fitting blades to its top should give greater radial dispersal.

The speed and diameter of the auger will affect the rate of flow; they vary considerably according to make.

Mixing Chamber: the dimensions of the cylindrical chamber are varied, but the capacity should be greater than the working capacity to allow for increased bulkiness by aeration, in practice about 85% of the total capacity is filled. The slope to the hopper should be steep enough to overcome the internal friction of the meals, i.e. greater than their angle of repose, otherwise the meal cannot flow by gravity.

Table 3 gives data for a selection of vertical meal mixers with capacities up to 15 cwt. and the range of dimensions is readily apparent. From this it would appear that either little co-ordinated fundamental research had been done, or design had little effect on uniformity of mixing.

Power Drive: the drive is normally taken to the top of the auger, either directly by Vee-belts from a side-mounted motor or through bevel gears and a lineshaft. The horsepower required depends upon the mixer capacity and the auger speed; a 5 cwt. mixer would require about 1 - 2 h.p.and a 10 cwt. mixer 2 - 4 h.p.

3.5 Counter-current mixer.

This machine manufactured by Nauta of Haarlem, Holland is designed on the vertical auger principle, but the auger is arranged to revolve around the side walls of the conical mixer chamber (see Fig.8). The auger itself is rotated by a worm gear drive at the bottom of the machine, the circular motion around the chamber being provided by a bevel gear drive through an arm inside the chamber to the top of the auger. The resulting counter-current movement imparted to the material in a vertical and horizontal direction was claimed to give a more efficient and uniform mixing.

Make & Capacity	Position of feed	Type of Auger	Speed r.p.m.	Auger dia. in.	Pitch in.	Cone Slope Angle	Ratio of body height dia.	Ratio of Volume Body/ cone	Total Volume ft^3	Rated Vol. as % of Total Volume	H.P.
Christy & Morris 5 cwt	Top	plain	40	10	12	64^o	1.4	4.5	21	85	2
I.P.U.Mixator 5 cwt	Bottom Top Disch.	shrouded with spreaders	300	9	8	66^o	1.9	6.4	18	95	1
Woolley 5 cwt.	Bottom Top Disch.	shrouded	240	9	12	54^o	0.5	4.9	23	85	3
Booth Conical 10 cwt.	Top	plain	85	16	12	67^o	0.7	1.8	50	70	4
Booth "self charge" 10 cwt.	Bottom	plain	85	16	12	67^o	0.7	1.8	53	70	4
Christy & Norris 10 cwt.	Top	plain	40	12	12	64^o	1.7	5.2	42	85	3
Albion "Vertex" 10 cwt.	Bottom side elevator	plain	150	12	9	60^o	0.5	1.4	50	70	2
Reffold 10-12 cwt	Bottom	shrouded with spreaders	280	9	6	63^o	0.8	3.7	45	80	4
Woolley 10-15 cwt.	Bottom	shrouded	240	9	12	54^o	1.2	10.2	51	70	3
Whitlock 10-15 cwt.	Bottom	shrouded with spreader	320	9	6	61^o	0.5	2.2	51	70	3

Table 3. Some dimensional data of vertical auger mixers.

3.6 Horizontal auger mixers.

The trough type of batch mixer is an example of convective mixing, the batch of meals is continually agitated by a rotating worm or set of spirally arranged agitator blades. This type of mixer is suitable for mixing wet materials as well as dry and claimed to be particularly suitable for mixing materials of varying density and particle size. See Fig. 9 for an example of horizontal mixers.

Hebblethwaite[37] proved in a mixing trial that a horizontal machine achieved a good mix in less time than a vertical one, but it required considerably more power and was more expensive to purchase.

Feed and Discharge: generally the components are fed into the trough from above or one end and discharged after mixing by gravity from the bottom of the trough, or by tipping the trough like a cement mixer, or by using a conveyor away from the machine.

Mixing Mechanism: mixing is performed by auger flights or spirally-mounted blades on a horizontal shaft, they are arranged to give alternatively right and left-handed rotary motion to the meals in order to prevent segregation at one end. In this way the batch is continually turned over and thrown backwards and forward so that mixing may proceed. The speed of the shaft is slower than that of the vertical type, being about 30 - 40 r.p.m., whilst the power required varies from about 40 h.p. for a one ton batch containing molasses to a range of 20 - 30 h.p. when mixing similar batches of dry components only.

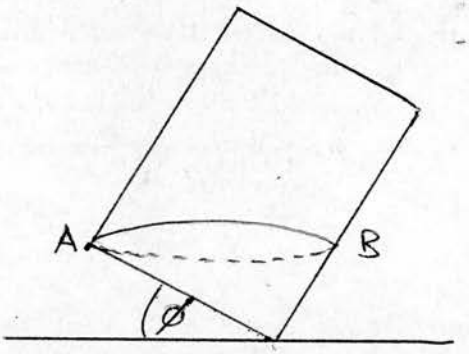
An alternate form of this mixing mechanism makes use of two augers in parallel and rotating in counter-clockwise directions and so conveying the meals backwards and forwards until they are thoroughly mixed. When mixing molasses they need to be heated to ensure easy flow, whilst a metering tank distributes the liquid over the meal via a perforated tray ; alternatively a pump and spray nozzle is employed.

3.7 Drum Mixers.

Variations on this type of mixer include the inclined drum or barrel and

the box with non-symmetrically located supports used for seed treating. This diffusive mixer is mainly suitable for chemicals since their particle shape is comparatively constant. Coulson and Maitra[29] experimented with a drum mixer and found that the maximum capacity that could be mixed was such that it formed as eliptical surface at A (Fig.10).

Fig. 10.
Drum mixer diagram.



Above this level there was virturally no chance of mixing occurring. From this it followed that the drum should have a length to diameter ratio of 3/2. The angle of inclination, ϕ, was optimum at 23° and for angles 8° and 30° the mix was never highly dispersed. Examining drum speeds between O and 100 r.p.m. It was found that a low speeds dispersion was poor as particles were not carried to the top of the free surface with sufficient momentum to roll rapidly across it. The critical speed occurred when the whole mass rotated around with the drum, but in practice it was advisable to operate as near this speed as possible - 55 r.p.m.

Other discoveries included the facts that the smaller the particles the quicker the rate of mixing and that the greater the difference in ingredient proportions the more difficult was mixing. As the particle size ratio increased the small particles slipped through the voids between the large particles, so that it became increasingly more difficult to obtain an intimate mix, but such mixing as was achieved effected rapidly. With some systems the stable condition was one of separation with the coarse particles uppermost, in which case the time of mixing had to be judged accurately otherwise separation would occur - particularly in systems of different particle size or

of widely different density.

Experiments showed that more rapid mixing was effected if the materials were fed simultaneously into the drum than one after the other.

In their experiments, Blumberg and Maritz[24] used a drum with a length to diameter ratio of 3/2 and speed 55 r.p.m. but gave no reason for making $\phi = 30^{\circ}$.

3.8 Muller-type mixers.

These were described by Bullock[38] as being suitable for wet and dry materials over a wide range of densities and viscosities. They are intensive mixers since they break down aggregates. A muller mixer consists of a drum for the batch, one or two muller wheels for rubbing and crushing the material, and inside and outside ploughs to fold over the material and return it to the muller path. They are obtainable with fixed or rotary pans in addition to the rotor with the muller wheels attached to it.

3.9 Convergence-divergence mixers.

The principle of convergence-divergence (C-D) implies a continuous "giving" and "taking" reaction. Constructions based on this principle, which is not rigid, comprise components which are complementary in pairs, each component having a series of continuous variations of configuration between maximum values and zero.

In its simplest form the C-D mixer consists of a Y-shaped container rotating about an axis as shown in Fig. 11. Convergence occurs when the material is collected in the "trunk" of the mixer, but on rotation divergence into the "arms" splits the mix into two portions. Continual rotation brings about the mixing action by this alternate collecting and splitting of the mix.

The C-D principle can also be incorporated into contra-rotary auger conveyors of the type designed by Frenkel[39] in three basic constructions. The first construction being adaptable to continuous crushing or mixing by extrusion; the second being suitable for batch mixing or dynamic seals and the third incorporates the previous two constructions to give combined mixing,

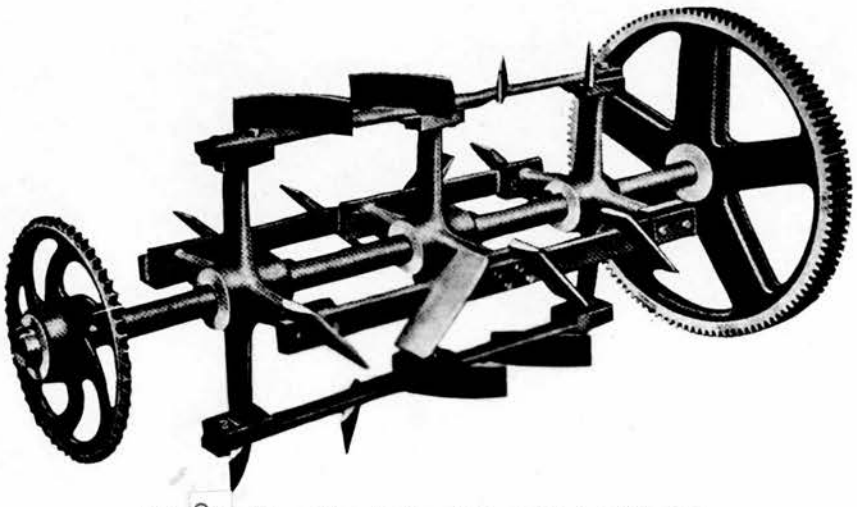


FIG. 9a—The mixing blades of Barron horizontal mixer.

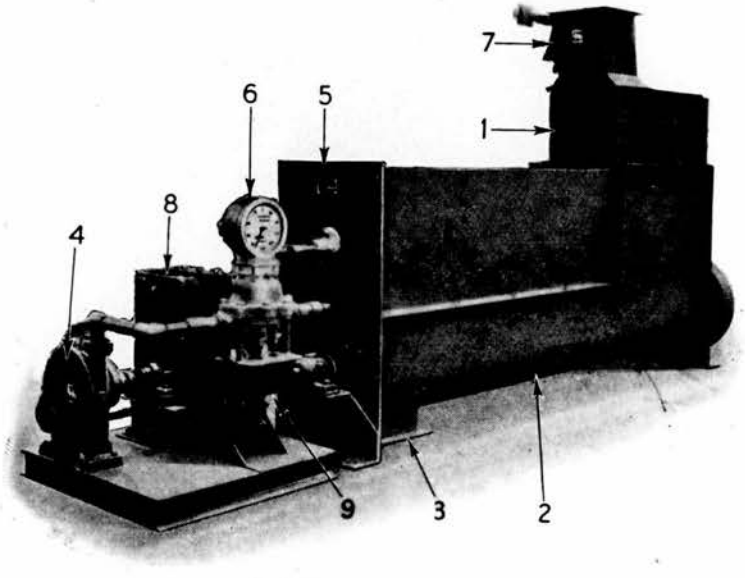


FIG. 9b—The Simon cascade mixer.

1. Feed worm. 2. Mixing chamber containing cascade worm. 3. Meal outlet. 4. Molasses regulator. 5. Molasses and steam atomiser. 6. Molasses meter. 7. Meal spout flow indicator. 8. Stop and start unit. 9. Electro-magnetic steam valve.

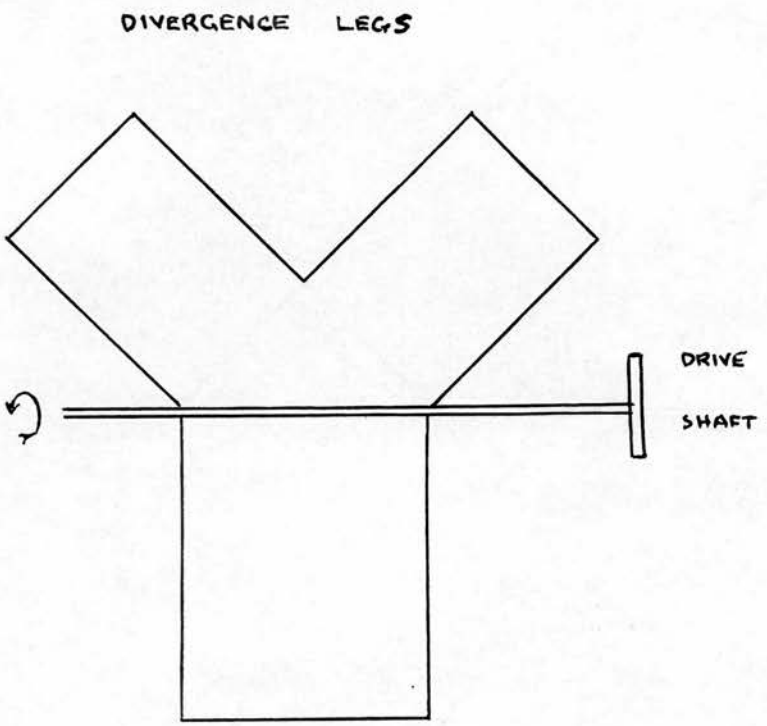


FIG. 11.

Y-TYPE MIXER

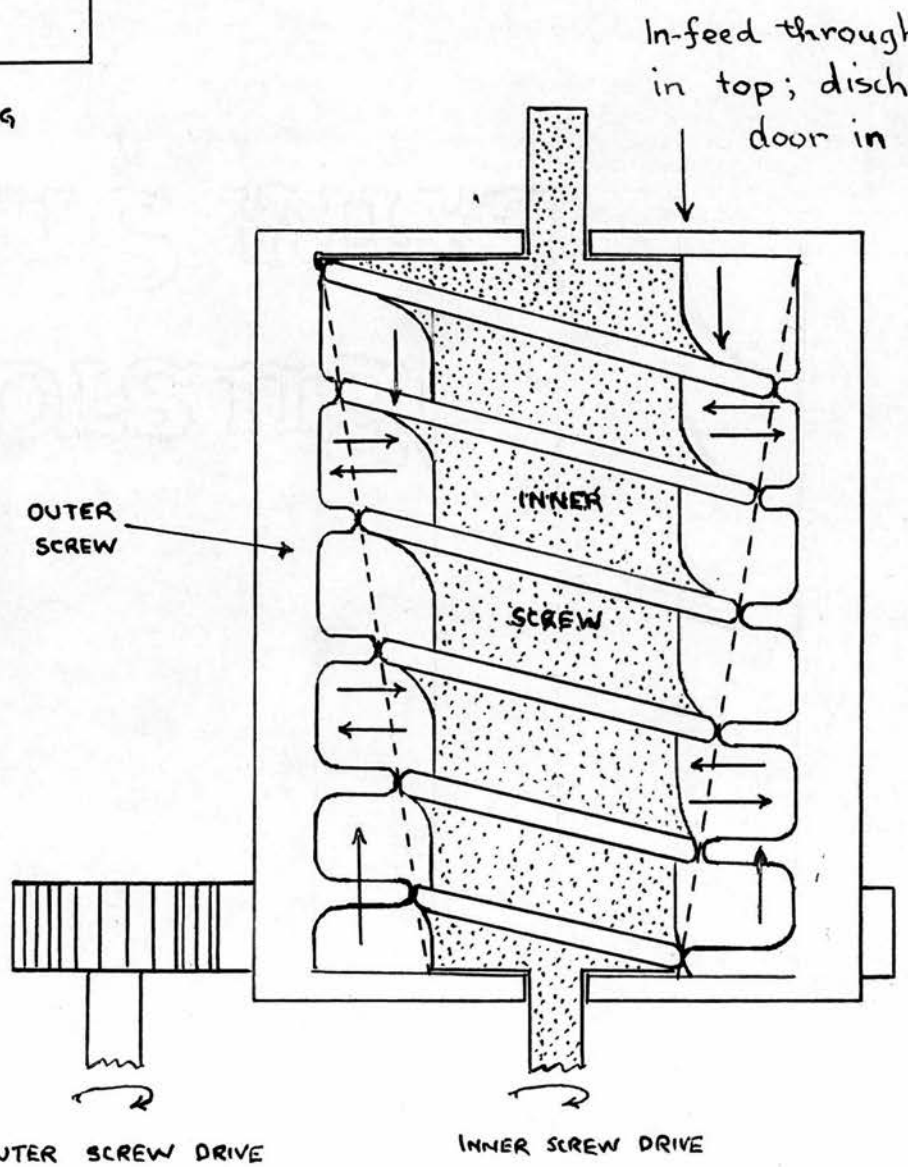


FIG. 12.

DOUBLE-SCREW TYPE

crushing and extrusion.

Fig.12 shows the second construction applied to a batch mixer. It makes use of a pair of contra-rotary components having such a series of variations in configuration that "giving" and "taking" effects between them are provided simultaneously. Each component of the pair has a similar series of groove cross-section between maximum and zero, thus providing the first feature of convergence. Since precision is unnecessary even though all particles are treated, there is a process of increasing similarity which satisfies the second feature of convergence.

Divergence is effected by reversing the series of groove cross-sections in the two components and by driving the augers in opposite directions. Consequently whilst convergence occurs within each groove, the contents of each groove are being diverted continuously into adjacent grooves. Adjustment of clearance can be made and satisfactory mixing occurs with appropriate auger design even without rotation of the outer member.

Qualitative mixing in addition to quantitative mixing can also be provided by the C-D principle; Frenkel[40] explained that concentric mixers could crush the materials to give equal numbers of particles in each ingredient proportion. They were then extruded into a single C-D mixer where uniformity resulting from the association of single particles could satisfy the smallest possible scale of scrutiny.

Continuous feeding is possible and the rotors can be adjusted to suit the size reduction required for each ingredient. Qualitative mixing may not be applied to mixing animal feeding stuffs yet, because there is evidence that different animals require meals of different particle size. In fact in some cases flaked or crushed grains are added to keep the meal "open".

3.10 Continuous Mixers.

In the large automatic plants it is essential for control and economy to have continuous mixing. The method employed is the blending of ingredients by feeding them continuously into an auger conveyor in the correct proportions.

The small proportion ingredients are pre-mixed before blending with the main ingredients in order to increase the efficiency of distribution.

There are two methods of incorporating the ingredients, by weight, and by volume. The former is more accurate as it is not affected by meal densities, but it is much more expensive to instal due to the necessary complication of the automatic continuous weigher. The volumetric method is much simpler and is considered to be sufficiently accurate at the present. - the Ministry of Agriculture allows a 10% margin of error for the protein value and 8% for the oil and fibre values in marketed animal feeding stuffs.

4. THE EXPERIMENTAL PROCEDURE.

OBJECTS OF RESEARCH.

4.1 The study of the mixing of animal feeding stuffs was carried out experimentally in three sections; (1) an examination of the properties of the meals that make up feeding stuffs; (2) an investigation of the effect of the mixing mechanism on the uniformity of mixing; (3) an investigation of the effect of the meals themselves on the uniformity of mixing. However, before proceeding with these investigations it was necessary to develop and test methods of assessing uniformity and to design and construct a mixer suitable for this work.

To reduce the number of variables it was decided to examine one type of meal mixer only and the vertical auger-type was chosen. It appeared to satisfy most farm requirements and was the commonest type found in Britain and the U.S.A., but its design was open to investigation as manufacturers incorporated a range of different features designed to improve the efficiency of mixing. The experiments were planned to investigate these features, in addition to studying the effect of the various properties of meals on the mixing process, and it was hoped to draw conclusions which would assist the compounder of feeding stuffs to improve his products. It was hoped also that this study would provide a basis for further investigations, particularly testing compound feeding stuffs and examining the effect of mixing uniformity on the feeding of animals.

4.2 A summary of the Research Objects.

(1) The development of techniques for measuring the uniformity of feeding stuffs.

(a) to produce a suitable sampling technique for meal mixes.
(b) to investigate methods of tracing individual components in a mix in order to assess the uniformity of that mix.

(2) The examination of the properties of meals.

(a) to determine and analyse the size and shape characteristics of meal particles.
(b) to obtain the fineness and uniformity moduli of each meal.

(2) The examination of the properties of meals. (Cont'd)

(c) to examine the effect of grinding on the size reduction of cereal grains when producing meals for mixing.
(d) to estimate the internal friction of meals.
(e) to examine and measure the viscosity of meals.
(f) to investigate the effect of moisture content on the viscosity of meals.
(g) to examine the porosity and bulkiness of meals.

(3) The investigation of design features that affect mixing in a vertical auger mixer.

(a) to construct and calibrate a scale model mixer.
(b) to observe the effect of time on the uniformity of mixing.
(c) to investigate the difference between top and bottom in-feed positions to the mixer.
(d) to investigate the effect of auger speed on the mixing process.
(e) to investigate the effect of different mixing chamber sizes on the mixing process.
(f) to investigate the effect of shrouding the auger.
(g) to investigate the effect of fitting spreading blades to the auger.
(h) to examine different types of mixing auger.

(4) The investigation of the relationship between the component meals and the process of mixing them.

(a) to investigate the effect of different component proportions on the uniformity of mixing two meals.
(b) to investigate the effect of meal viscosity on the uniformity of mixing.
(c) to investigate the effect of meal particle size and shape on the uniformity of mixing.
(d) to investigate the mixing of more than two components.
(e) to investigate the effect of non-uniform mixes on the feeding of animals.

ASSESSMENT OF THE UNIFORMITY OF MIXING.

4.3 The sampling of meal mixes depends upon the method of sampling and the size of sample to be taken. The samples can be drawn either from the mix in the mixer or from the mix during or after emptying; the former requires a sampling spear but is necessary procedure when investigating mixing over a period of time; whilst the latter methods are simpler, they can be used only

when mixing has finished. All three methods were investigated with a binary mix of barley meal and dried milk powder.

Several forms of sampling spear were considered including, the standard N.I.A.E. grain sampling spear; a pointed cylinder with rotary shutter; a hollow tube coupled to a suction pump; and a small auger with a cylindrical cover. After test the grain sampling spear with small modifications appeared to be quite satisfactory for withdrawing a sample of meal; the standard deviation was 11.4 gm. for an average sample of 129.9 gm. A diagram of the sampling spear is shown in Fig.13. The minimum number of samples which could represent the mix as a whole was determined to be five, one less than the number considered to be adequate by Michaels and Puzinaukas[27] when studying a horizontal paddle-type mixer - the results are shown fully in Appendix A.2. Repeatability of results from uniformity tests with five samples also showed that the sample size provided a sufficiently small scale of scrutiny. For analysis the samples had to be reduced in size by a centrifugal cone-type sampling machine, but there was no significant difference between sample and sub-sample at the 1% level of probability.

When comparing the methods of sampling a mixture of 50% barley meal and 50% dried grass meal was fed into the bottom of the model mixer and mixed with the shrouded auger at 195 r.p.m. After 35 mins. mixing five random samples were taken with the spear from the mixer,then five more whilst emptying the mixer by inserting a 150 ml. beaker into the flow of meal, and finally five more from the sacks after filling by using the spear. The results tabulated in Appendix A.2 showed that there was no significant difference between these three methods with respect to the uniformity of mixing.

4.4 Testing for Uniformity.

The Uniformity Index developed in section 2.24 was to be used to measure the degree of uniformity of a mix under the various conditions to be investigated, but a problem arose concerning the measurement of the actual amount of each component present in the mix. Due to the similarity between many of the components it was no simple matter to differentiate one from another in order to

assess the proportions of each, to which had to be added the requirements of the test itself, namely, that it should be reliable and simple to use and analyse in large numbers.

A large range of indicators were conceived, but the numbers were greatly reduced when taking into account that large quantities of edible material were being mixed, that ingredients must be traced individually, and that the analysis should be as practical as possible. The indicators investigated are described in the next few pages and their relative merits discussed.

1. Radioactive isotopes.

The use of radioactive isotopes was an obvious first choice as it was thought that the path of activated meals could be traced in addition to the assessment of uniformity. Great plans were conceived on this basis, but for safety reasons the elements to be activated had to produce short lived isotopes. Phosphorus with a half-life of 15 days had been used in many agricultural growth experiments, but this was considered too long-lived and potassium with a half-life of 12 hours was considered instead, also because it was present in several of the meals used in animal feeding stuffs.

The Atomic Energy Research Establishment at Harwell was contacted and the following paragraphs are summarised from correspondence with Jefferson and Wildblood of the Isotope Division.

The monitoring of the activity as it passed along conveyor belts was not a reliable indication of the distribution, but the monitoring of the gamma-activity of the bagged meals was much more reliable. Tests of this kind were not suitable for routine use and only considered for an infrequent check of the mixing capabilities of a plant.

Calculations were carried out and confirmed by Jefferson[41] that the amount of K_2O in barley meals was sufficient to be measured when activated. The standard aluminium canister held 23 grams of barley meal with content of 0.57% K_2O which meant a weight of 0.09 gm. K. Using Pile factor 6 the specific activity would be 1.46 mC per sample which would be reduced by 50%

on the return journey from Harwell. Uniform distribution of this sample in a 10 cwt. mix would give a gamma-activity of 3.31×10^{-5} mC per gram, which was equivalent to 7.5 counts per minute when allowing a 1% counting efficiency. Unfortunately, the count rate was further reduced by a factor of 10 on account of the geometric arrangement of the sample and the counter. Consequently, the soaking of the meal in sodium bicarbonate was suggested, however, drying out the sample and crystalline deposits caused it to differ considerably from its natural state.

These facts, plus the discouragement of activating meals by Wildblood[42], not only because of some constituents which activated into long-lived isotopes, but also because of the unknown hazard which might arise from the production of carcinagenic substances, suggested that this method was not entirely satisfactory and it was discarded.

Later on tests were carried out by Wildblood, Foll and Harris[43] with activated minerals representing synthetic vitamins in layers' mash mixes. 2¾ oz. free flowing mineral was added to 20 cwt. meal and mixed in a vertical mixer for 10 minutes. Each 1 cwt. bag was checked with a scintillation counter for activity and there was under 5% variation from the average in any bag. Taking 5 oz. samples to represent a hen's daily ration this showed that each would be satisfactorily vitaminised. The main disadvantage to this work was that the results obtained for physical properties of minerals and vitamin supplements in section 5.2 and 5.5 showed that they differ quite markedly.

2. Dyestuffs.

The addition of concentrated dyes to the meals and determining the amount of dye present in each sample by colour absorption showed great possibilities as a means of assessing the degree of mixing. An advantage was that up to three colours could be used at a time provided that there was sufficient difference between their wavelengths.

Tests were carried out with non-toxic water soluble dyes supplied by I.C.I.Ltd., Manchester, and they were the following:-

Dye	Colour Index	Designation
Amaranth	No. 184	Red No. 4
Tartrazine	No. 640	Yellow No.17
Blue X S	No. 672	Blue No. 24

The dyes were extracted in squeous solutions and they were estimated against dye solutions of known concentration. Blank extracts were prepared for the comparison in order to ensure that the natural colours of the ingredients did not introduce a possible source of error. The colour estimation was performed with an E.E.L. Absorptiometer and results for dyes diluted by distilled water to one part in 100,000 by weight are shown in Table 4.

The most suitable filters for these three dyes were Nos. 303, 607, and 623 and they were used for subsequent tests. The probability of the values for the 50-50 mixtures compared with the mean range from .001 to .01 which showed that two dyes could be estimated from one filter reading.

Exact amounts of dye were then incorporated with meal samples, some by spraying and re-drying the meal and some by mixing in the dye in powder form. The dye was then extracted with water and made up to a strength that would represent one part in 100,000 if all the dye was completely extracted. The results are shown in Table 5.

TABLE 4.

COLOUR ESTIMATION OF DYES ALONE

Dyes	Filter Colour and Ilford No.							
	Red 205	Blue 303	Green 404	Red 607	Red 608	Blue 623	624	625
Blue XS	22.9	7.0	18.0	40.5	10.9	6.0	-	-
Amaranth		34.5	31.8	3.0	0.5	39.0	38.5	32.7
Tartrazine	Nil	8.8	Nil	Nil	Nil	5.4	Nil	Nil
½ Blue + ½ Amaranth)		25.1		21.1		22.3		
½ Tartrazine + ½ Amaranth)		24.5			17.5		24.0	

TABLE 5.

COLOUR ESTIMATION OF DYES EXTRACTED FROM MEALS

Dyes	Barley Meal		Wheat Meal		Bean Meal	
	EEL Units	% recovery	EEL Units	% recovery	EEL Units	% recovery
Blue XS	11.7	28.6	11.4	27. 7	10.5	25.5
Amaranth	11.3	29.0	10.9	28.0	9.8	25.0
Tartrazine	2.9	32.9	2.7	30.7	2.4	27.2

The recovery ranged between 25% and 33% due to the dyes having an affinity for the meal, particularly protein. Consequently, results vary from meal to meal for the same dye. A slight improvement resulted from using an aqueous ammonia solution for extraction, but under certain conditions the ammonia coagulated the proteins and obscured the light passage. Further tests were carried out with solvent soluble dyes, namely Lithofor Yellow AS, Waxoline Red OS and Waxoline Blue AS. Nearly 90% recovery was possible, but the solvent also extracted oils and pigments from the meals and the use of blank extracts was essential. Unfortunately these dyes were toxic and dyed meals had to be discarded.

During the latter tests the extraction of pigments showed that meals themselves could be used as tracers without the inherent experimental errors due to the addition of dyestuffs to them and this estimation was considered more satisfactory provided a test could be devised.

Hebblethwaite[44] also experienced difficulty with the extraction of dyes, his recovery of black dye from barley meal was 30.7%. He later used other solvents to eliminate absorption and obtained dye recoveries in the region of 94%.

Chromium sesquioxide had been used by Chanda[45] in digestibility trials, it was completely inert to the digestive juices and could be recovered by burning the sample and analysing the ash. This method was only considered as a last resort.

3. Pigments.

All meals contain pigments called Chromogens and each meal has its own specific chromogen. The estimation was by analysis after extraction with acetone. Unfortunately tests showed that the quantities of chromogen present in any meal was so small that the minimum sample size was in the order of 15-20 lbs. for reliable estimation. However, there was an exception in the form of chlorophyll which was present in appreciable quantities in dried grass meal.

The standard method of extracting chlorophyll is with petrol ether and this was used without heating in the initial tests, which are recorded in Appendix A.3. A straight line graph that passed through the origin and having a slope of 1.10 was obtained by plotting the weight of dried grass against its colorimeter deflection. When 5 lb. of dried grass meal was added to each of two mixes it became more uniformly mixed with the passage of time. The small number of readings limited the data that could be obtained from these tests, however, they did prove that the chlorophyll extraction from dried grass was a valid method of assessing the uniformity of mixing.

In addition to chlorophyll, other pigments of plants included the carotinoids or lipochromes, described by Knowles and Watkins[47] as being responsible for many of the yellow and orange hues in nature. They could be separated by methods evolved by Mann[48] but were not tested due to the small amounts found in meals.

4. Chemical Tracers.

Because minerals were added to feeding stuffs certain chemical elements and radicals could be assessed by simple chemical tests. The most suitable for testing meal mixes were:-

Free chloride from salt.
Free calcium from ground limestone.
Phosphoric acid from bone flour.

The first suggestion was the easiest to test and was analysed by a modified

Mohr's method as recorded by Lowry and Cavell[49]. When testing mixtures of barley meal and butter salt the amount of chlorine recovered was 90% and it was considered in Appendix A.4 to be a satisfactory method of estimating the amount of salt in a meal mixture.

Chanda[45] used chromium sesquioxide in determining the digestibility of carotene, it was inert and gave a yellow colouration, or burnt with a green flame. Potassium iodide was another suitable chemical tracer as it was readily absorbed, water soluble and could be detected easily by the starch test. Alternatively potassium iodide could be used to trace a starchy component in a mix by its Iodine Blue Value - method credited to Bourne[50] which had been modified by MacDonald[51] for use with cereal meals. The examination of this method is recorded in Appendix A.5 where it was noted that it could be used only for a meal containing starch in the presence of components that did not, e.g. skimmed milk powder.

Lactose is present only in milk and milk products consequently it could be used to trace components such as skimmed milk and whey powders by the estimation of reducing sugars present. The iodimetric determination for lactose was used according to a test of Hinton and Macara[52] and the original tests were quite satisfactory, but later the barley meal contained appreciable quantities of reducing sugars. This must have been due to hydrolysis of the starch by the enzyme diastase to produce Maltose which was a reducing sugar, the original tests were performed with new barley and the later ones performed after the barley had been stored for several months, during which time the hydrolysis could have occurred. Despite the initial promise of this method it had to be eliminated; the results of the examinations are given in Appendix A.6.

Other chemical methods of tracing components of a mix that were not examined experimentally were, (1) Barnhl's test modified by Winton[53] for testing the presence of wheat in a cereal mixture and based on the fact it is the only cereal containing any appreciable amount of gluten (8 - 12%) which can be estimated by staining with eosin; (2) the optical estimation of sugars; (3) the

use of organic chemicals, such as urea, to bring about additions to the NH_2 radical.

5. Biological Tracers.

The additions of toxic substances to meals and testing the reaction on small animals is worth only a mention because it did not appear to be a practical method of assessing the uniformity of mixing. However, one manufacturer did offer a similar case as proof of the mixing efficiency of his mixer. A farmer discovered coccidiosis amongst his flock of hens and mixed a small amount of sulpha-mezathine in the poultry meal to cure them. It was claimed that an overdose or underdose would cause a hen to die and as none died they must have all received a correct dose and the mixer must have produced a uniform mix. This test could have proved the uniformity of only one component and not the whole mix, also its validity as a test of uniformity was questioned. The Veterinary Department considered that it was doubtful if more than half the hens would have had coccidiosis and in any case one third of a dose was sufficient to provide a cure, whilst three times the dosage would not kill.

Tests of the uniformity of feeding stuffs could be carried out as feeding trials with the assessment based on Protein or Starch Equivalents or the complete analysis of the foods. This proved to be a satisfactory method of assessing uniformity as it has a practical value. It was used to investigate the effect of feeding non-uniform feeding stuffs to pigs.

Vitamin assays could be arranged but only Vitamins A and D could be assessed without tedious micro-analysis.

6. Fluorescent Tracers.

Fluorescene or zinc 8-hydroxyquinaline can be detected in very minute quantities and was used by Hebblethwaite[37] in mixing trials, by examining samples under ultra-violet light and assessing uniformity by numerical counts of the presence or absence of the tracer. The quantity added was 0.001% of the mix and this amount was insufficiently sensitive.

7. Physical properties of meals as tracers.

Where flaked material was added to the mix sieving should give an indication of its distribution provided all the flakes are greater than the other meal particles present. In practice this was unsuccessful because mixing trials with flaked maize alone showed that there was a 15% reduction in the Fineness Modulus after 20 minutes mixing in a vertical mixer. (Appendix A7.)

In the paragraphs on chemical tracers it was shown that the starchy properties of cereals could be used to estimate their presence in a mixture, the other main constituent of cereal grains was fibre and its properties were considered. The fibre content of oatmeal could be examined by sieving because the glumes were little affected by grinding processes, unfortunately all the fibre did not separate on one sieve nor completely alone, therefore this method was passed over in favour of the Crampton and Maynard[54] method of cellulose analysis. Although satisfactory this determination proved too tedious and lengthy for repetitive analysis and the time for acid digestion quite critical; so the simpler and less critical method of Walker and Hepburn[55] known as Normal Acid Fibre Determination was adopted instead. By using the starch and fibre tests in combination it was found to be possible to examine the behaviour of different particles of the same meal. Results of cellulose and fibre examinations are recorded in Appendix A8.

Insufficient data had been obtained to use the physical property differences of meals to consider this as a method of assessing uniformity and the same could be said of adding liquids, like cod liver oil, to mixes of fine particles.

Conclusions.

The procedures for tracing individual components in a mix that could be considered to give a satisfactory assessment of the uniformity of that mix were the following -

(a) the addition of solvent soluble dyes for tracing cereal meals.
(b) the estimation of chlorophyll in samples containing dried grass.
(c) the Iodine Blue Test for distinguishing starchy and non-starchy components.
(d) the estimation of chlorine to test the presence of salt.

(e) the addition of fluorescent tracers in minute quantities.
(f) the Normal Acid Fibre Test for tracing fibrous meal particles.

In addition to the list above the uniformity of a mix was tested by complete analysis for protein, oil, fibre, nitrogen free extracts, mineral matter and moisture. This method provided an assessment independent of the basic ingredients of a mix and needed further investigation to evaluate its usefulness.

EXAMINATION OF THE PROPERTIES OF MEALS.

4.5 Particle size and shape characters.

The range of meals used in mixing animal feeding stuffs varied so widely that a complete investigation of them all was beyond the scope of this study. However, the fundamental physical properties of the following meals were studied in order to determine those most suitable for examining during the mixing process.

Cereal meals: wheat, oats, barley, maize, millet.
Pulse Meals: horse-bean, soya-bean
Other vegetable meals: groundnut, dried-grass, molasses.
Animal meals: fish, meat, bone, milk, whey.
Supplements: minerals, antibiotics, salt.

The sizes of the particles for all meals were obtained by sieving, the merits of sieving as a means of analysing meals was discussed in section 2.6 and design of sieves and sieve shakers were compared in section 2.10. In order to obtain the Fineness Modulus of meals according to the A.S.A.E.[13] recommendation a nest of sieves was obtained whose dimensions are given in Table 6.

TABLE 6.

Sieve size or number.	Sieve aperture Microns	Millimetre	Inches
$\frac{3}{8}$ in	9520	9.520	0.3750
4	4760	4.760	0.1870
8	2380	2.380	0.0937
16	1190	1.190	0.0469
300	590	0.590	0.0232
50	297	0.297	0.0117
100	139	0.149	0.0059
200	74	0.074	0.0029

The mechanical method of sieving was adopted which required the construction of a suitable sieve shaker and the development of a procedure for analysing the results.

The sieve shaker was designed to operate at 1400 vibrations per minute at an amplitude of 0.05 in., the vibrations being produced by a pair of 'out-of-balance' weights on a belt-driven shaft as shown in Fig.15. The sieves were carried in a rubber-lined framework mounted by four coil springs to a wooden base-board, whilst two adjustable rods and a clamping bracket held the sieves firmly in place. The power was supplied by a $\frac{1}{4}$ h.p. electric motor to which was incorporated a time switch; the standard sieving time was set at 5 minutes as a result of experimentation on the efficiency of separation with samples of 100 grams.

At first the meal particles tended to accumulate on one side of the sieves, this was attributed to the 'hammer' effect of the out-of-balance vibrator. After various modifications it was found that inclining the nest of sieves to the vertical created a rotary motion during vibration, so that the meal continually moved around the sieves instead of staying at one side. The optimum angle of inclination was found by trial and error, its value being $4\frac{1}{2}^{o}$.

This improvement in shaker design gave it an efficiency of 71% according to the Fahrenwald and Stockdale[10] method of estimation.

The sieve analysis was performed by sieving meal samples weighing approximately 100 grams for five minutes and the results calculated as percentage sieve fractions retained below each screen. Repeating the sieve tests showed that a minimum of three analyses were needed to obtain satisfactory mean figures for determining the fineness and uniformity moduli of each meal. These moduli indicated only the mean particle size and the range of particle sizes for each meal, consequently additional tests were required to determine the shape and surface area of particles.

Particle shapes had been related theoretically to equivalent spheres or equi-dimensional particles, whereas in practice they were irregular, which necessitated

the introduction of shape factors as described in section 2.8. The two coefficients, C and f, representing the volume and surface variations respectively, were required before the Specific Surface, S, could be determined; S was a measure of the surface area for a given weight of particles and, consequently, it must be a measure of the mixability of a meal because mixing was a function of the inter-surface reaction of particles. The procedure for determining the Specific Surface was based on microscopic examination of meal particles.

The partical demensions, length (L) breadth (b) and thickness (T) were determined with a microscope. A small sample of each meal was placed into a glass slide cavity, water added and then sealed with a cover glass. The slide was then clipped into the vernier-type adjustable table on the micro-meter. The vernier scales were set at right-angles and calibrated in millimeters; for small sizes of particle a micrometer eyepiece was used to give dimensions to the nearest micron. Calibration of the fine eyepiece adjustment enabled the particle thickness to be estimated fairly accurately, the thickness was taken to be the range over which some part of the particle was always in focus.

Surface factor was calculated from the equation

$$S = \frac{f}{p\,C\,d_p}$$

Where p = true particle density and d_p = projected particle diameter. Up to twenty particles were examined at random in each slide sample and a minimum of ten samples were drawn from each meal, this meant that between 200 and 400 particles were examined from each meal and the investigation involved several thousand measurements altogether. Consequently, to reduce the data collected the ratios for flakiness (h) and elongation (n) were calculated directly and fed into a calculating machine to reduce the recording to a minimum. The relationship between S and d_p was tested experimentally.

4.6 The Fineness and Uniformity Moduli.

The F.M. of a meal was determined by sieving it for five minutes in a nest of sieves comprising the following aperture sizes:- $\frac{3}{8}$ in., numbers 4, 8, 16, 30, 50, 100 and the pan. The vibratory shaker provided the means of shaking

the sieves which were made of brass by Endecott. After sieving the nest of sieves was dismantled and each sieve emptied into the weighing pan which was larger than the sieves. As each was removed from the stack it was given two sharp taps by hand to dislodge fine particles adhering to the underside and to ensure complete emptying of the sieves the apertures were cleaned with a small brush.

The material retained by each sieve was weighed in grams to the nearest decimal place and the complete sieve analysis calculated on a percentage by weight basis. Then the F.M. was obtained from each analysis according to the method given in section 2.12: the F.M. was a measure of the mean particle diameter d_l, whilst the U.M. gave an indication of the range of particle sizes as described in section 2.13. A value for d_l based on the sieve aperture sizes was calculated and compared with d_p from the microscopic examinations.

Since the experimental mixer was a half-scale model it was considered necessary to examine the properties of half-scale meals, for this reason the sieve apertures chosen were geometrically related - each sieve having an aperture area half that of the sieve above. Each half-scale meal was composed artificially of the same percentage weights as the full-scale meal, but on the next sieve down, e.g. using a nest of sieves with these aperture numbers - 4, 8, 16, 30, 50, 100, 200 and the pan. The correct percentage weights of each sieve fraction were then well-mixed to produce a half-scale meal suitable for the viscosity tests.

4.7 The effect of grinding on particle size.

All the cereal meals used during the experimental work were ground in a Christy and Norris "Briton" LB7 hammer-mill using four standard screen aperture sizes, namely 1/16", ⅛", 3/16" and ¼". Since the size of particles was a function of mixing ability it was decided to examine the F.M. of each of these meal sizes to discover if a relationship existed between the grinding screen size and the ultimate particle size. This would be important when considering the mixing of meals for different animals, for example the meals fed to pigs were more finely ground than those fed to cattle.

The use of different screen sizes in the grinder also provided a useful

means of examining the relationship between a mean particle diameter and its specific surface. By plotting the mean projected diameter, d_p, for particles of each size of grinding against the specific surface, S, the graphical result should be a straight line representing the equation $S = \frac{1}{dp}$. If this was the case the constants C and f, for volume and surface shape, held good for any size of grinding provided that the density of the meal remained constant. The values of d_1 could also be plotted against S in order to check the relation between the two mean diameters d_1 and d_p.

4.8 The estimation of the internal friction of meals.

The friction between any two surfaces in contact provides a force sufficient to hold them together until it is exceeded by any greater force applied externally. For example the force applied to meals by the mixing auger does not move the particles until it exceeds the frictional force between the particles; likewise particles on a tilted plane will not slide until the force of gravity exceeds the friction between the particles and the plane by increasing the slope. The critical angle where gravity overcomes friction is called the 'angle of limiting friction' and is a measure of the coefficient of friction between any two surfaces.

The friction between particle surfaces was a function of viscosity and the mixing ability; since it could not be measured directly it was determined relatively by testing the angle of limiting friction or 'angle of repose' as it is called with particulate materials. The apparatus used for this test consisted of an adjustable inclined plane from a mechanics set to which was fixed a container filled with meal level to the brim. The plane was inclined gradually until the meal just spilled out of the container and the angle of inclination represented the angle of repose, Y, for each meal. Values for Y were obtained for eachof the meals selected for the mixing trials and for mixture containing equal parts of two components in order to examine the interaction effect of meals on their friction coefficients.

Since the angle of repose was the minimum angle of inclination of the

meal surface that allowed the particles to flow over one another, it was the angle that a batch of meal would assume when poured into a heap or emptied from a bin. Consequently the hoppered bottom to the mixing chamber of vertical mixers should have a greater angle of inclination than the angle of repose of the meals to be mixed. It was assumed that mixer manufacturers had considered this fact and so the expected angles of repose should range between 50° and 70° as shown in Table 3 in section 3.4.

4.9 The examination of the viscosity of meals.

The viscous flow of meals was discussed in section 2.20 where a relationship between rate of flow and viscosity was derived. Viscosity of a fluid was defined as a measure of its resistance to shear or angular deformation, thus its dimensions must be force per unit area divided by velocity gradient. In the metric absolute system this becomes

$$(\text{dynes/cm}^2) = (\text{cm/sec}) \;/\; \text{cm} = \text{dyne-sec/cm}^2$$

N.B. The unit of absolute viscosity is the poise (or centipoise = 0.01 poise) and the viscosity of water at 68.4°F is one centipoise.

In practice it was more satisfactory to dispense with the absolute units by eliminating force, giving Kinematic Viscosity, u_k, in the dimensions of time and length only.

$$\text{Kinematic Viscosity} = \frac{\text{Absolute Viscosity}}{\text{Density}}$$

The metric unit is the stoke; where 1 stoke = 1 cm^2/sec.

Since the standard procedure for measuring either absolute or kinematic viscosity was a difficult and tedious process, simpler procedures had been developed for commercial operation. The commonest instruments in use being viscometers which measure rates of flow for liquids and derive kinematic viscosity from them. Viscometers must be calibrated against liquids of known viscosity and empirical equations used to obtain viscosity values for the fluid under observation.

The Redwood No. 2 viscometer for oils appeared to be the most suitable type of design as a basis for a meal viscometer. Its dimensions were too

small for meals - 100 ml capacity and 1.6 mm x 10 mm orifice - so an enlarged model was constructed. Experimentation proved that a minimum orifice of approximately 12 mm. diameter was necessary for the flow of most meals.

The first model was made from an inverted conical flask with a glass tube orifice. The conical development towards the orifice was necessary due to the steep angle of repose of the meals. Unfortunately 'bridging' prevented the flow of the coarsest materials despite the flask angle of $67\frac{1}{2}^{o}$, and it was concluded that the sides of a meal viscometer must not change direction at all if reliable readings were to be taken, consequently parallel-sided pipes were resorted to in subsequent models. (see Appendix A.9).

The Standard meal viscometer consisted of a drawn copper pipe, 12.8 mm. bore and 325 mm. long, and having an effective capacity of 415 ml. The pipe was fixed vertically to a wall-plate and fitted with a quick action gate-valve for emptying and a conical hopper for filling. The bore was cleaned and operated with sand before commencing the experiments.

The procedure for operating the viscometer was developed by trial and it commenced by closing the valve at the bottom and filling the pipe completely with meal; the pipe was then tapped sharply ten times to remove any air-locks and topped-up again. The orifice valve was designed for automatic operation of the timing device as shown in Fig. 14. As the hand-operated valve was swung open it contacted the carbon brush, B, and so completed the circuit to the electric clock motor because contact A was permanently fixed to the valve. The microswitch was closed by the pressure of the meal in the pipe against a thin plastic plate keeping the contacts together, however, when the pipe was empty the pressure was relieved and the spring-loading of the plate opened the switch contacts thereby breaking the circuit. The timing device was made accurate to the nearest tenth of a second by gearing up the clock hands, but in the light of later experimental results its response was hardly fast enough, particularly with the least viscous meals.

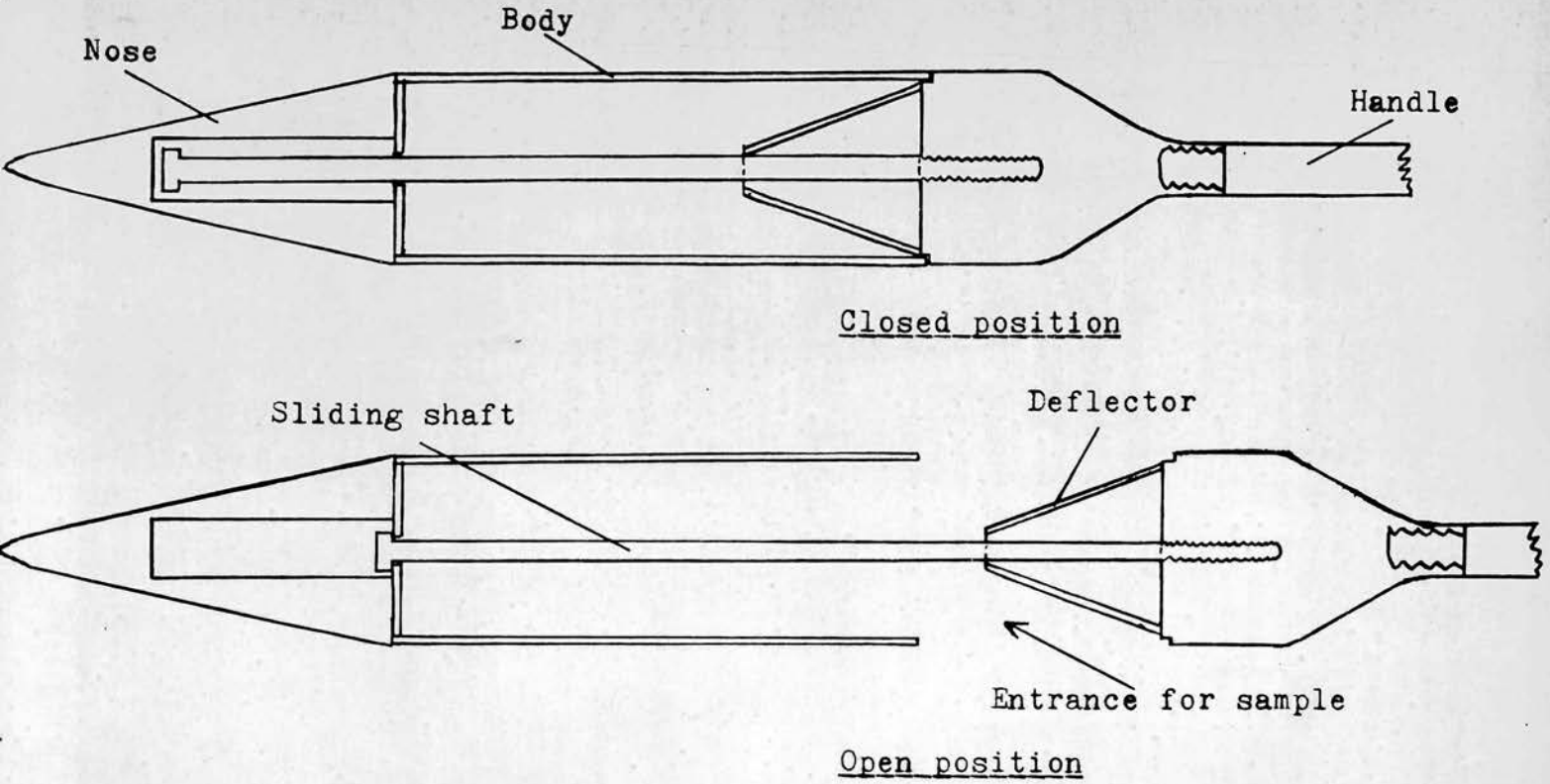


Fig. 13. The Sampling Spear

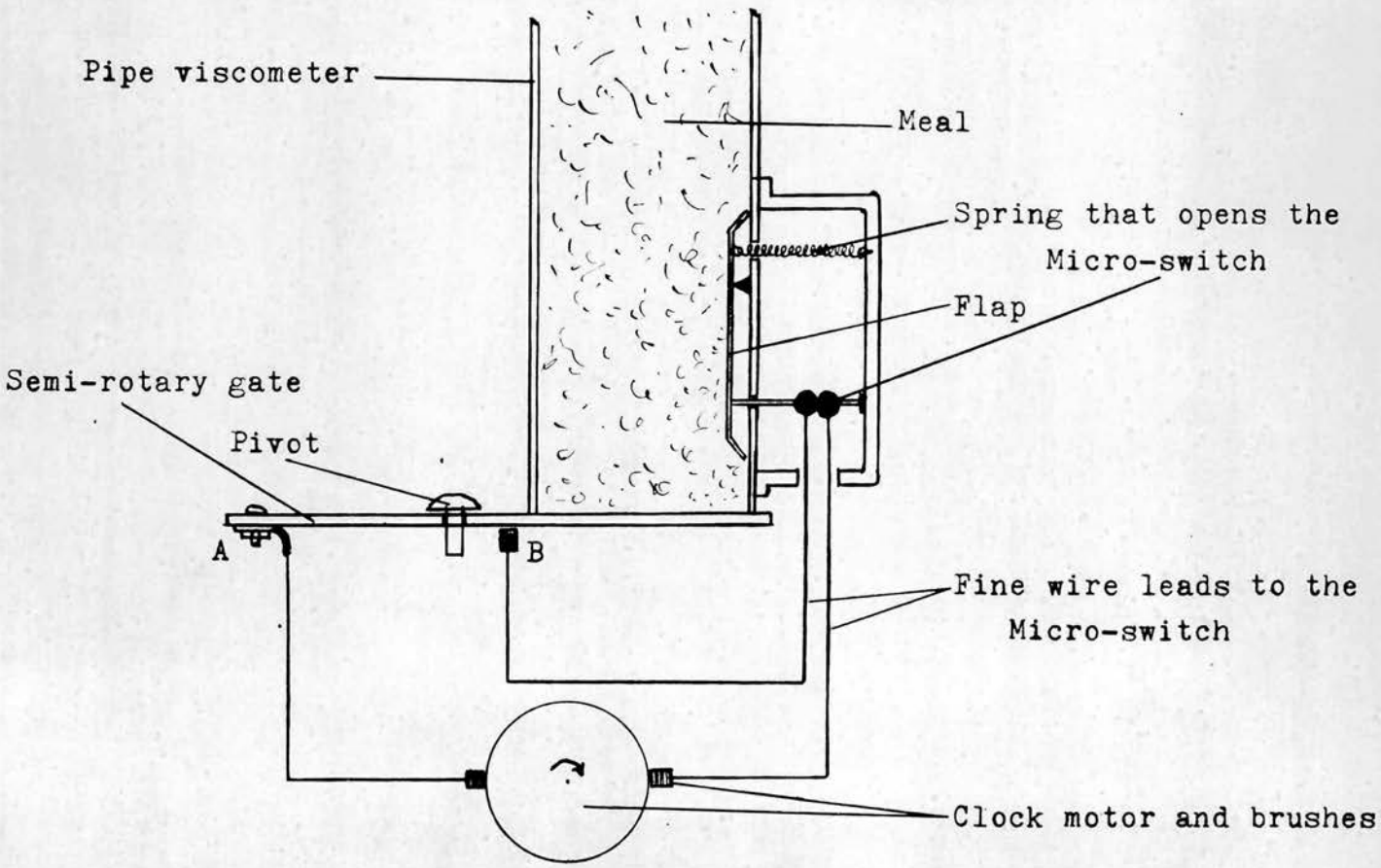


Fig. 14. Pipe Viscometer Orifice and Timing Mechanism.

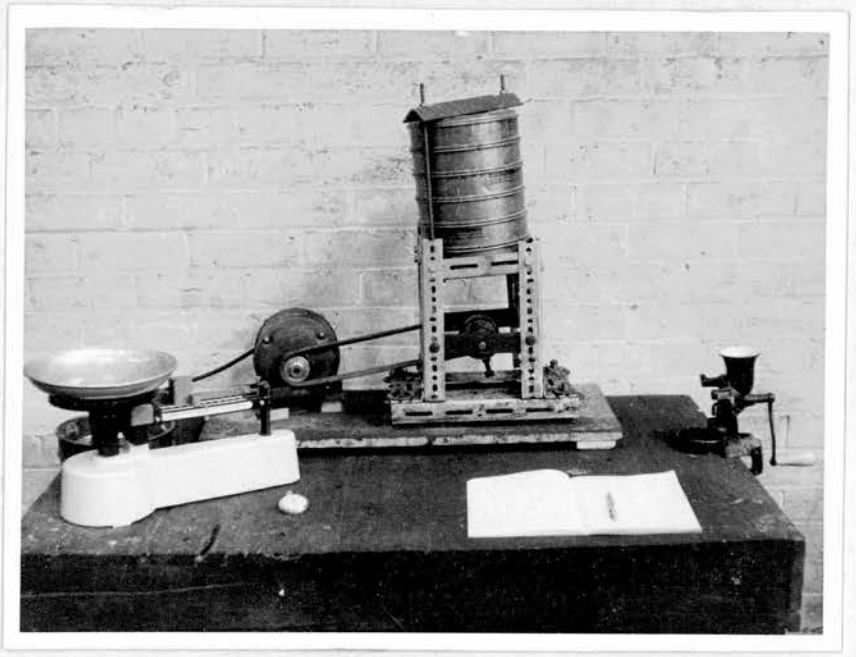


Fig. 15a The Sieve Shaker - showing the inclined sieves and the out-of-balance weight.

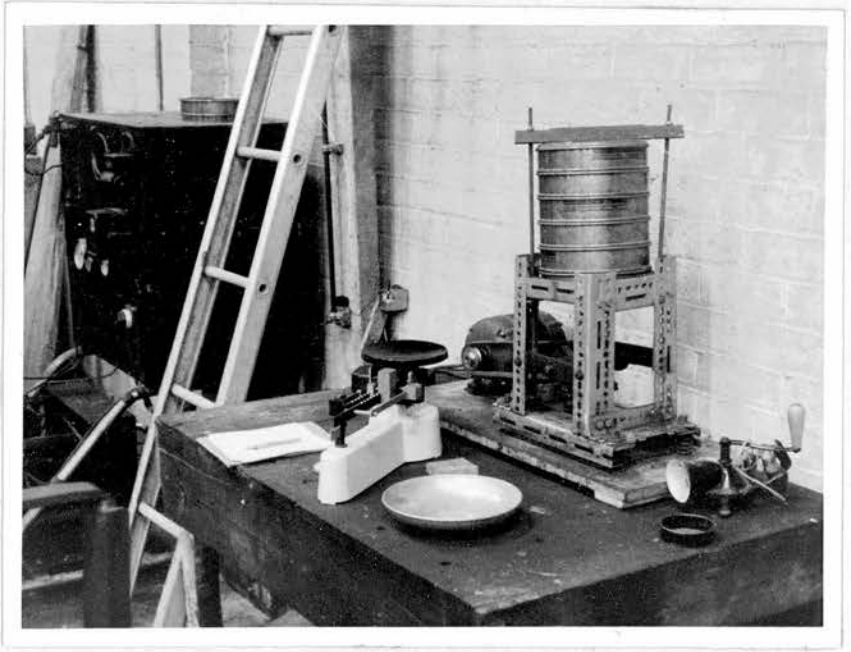


Fig. 15b The Sieve Shaker and ancilliary equipment. Note the spring mounting of the shaker.

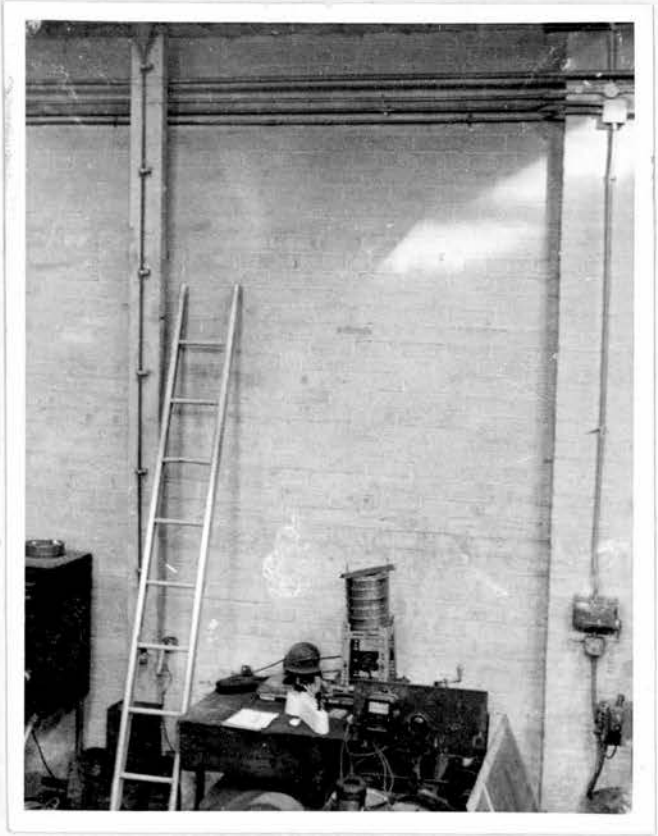


Fig. 16a The Small Pipe Viscometer.

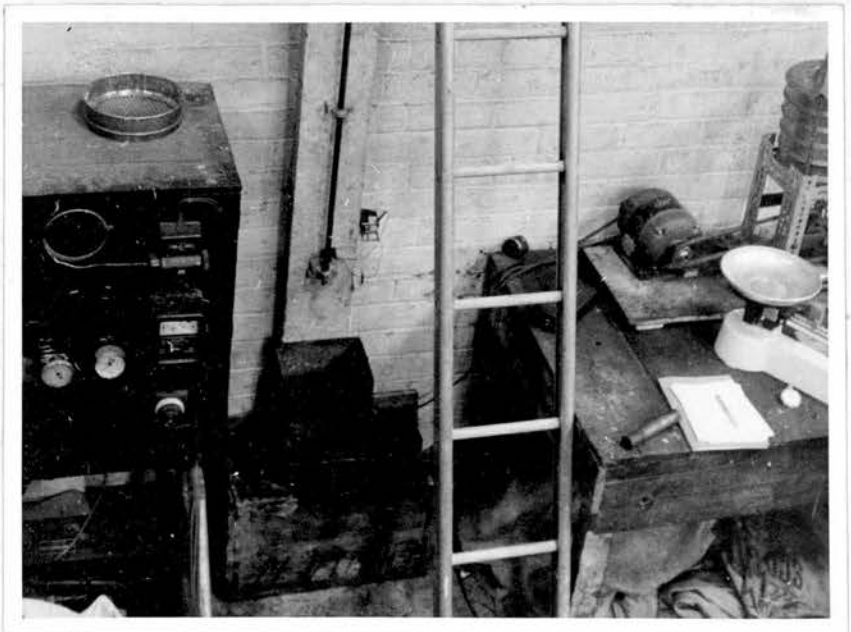


Fig. 16b The Small Pipe Viscometer Orifice and Timing Mechanism.

The rate of flow was recorded by subtracting the last time reading from the first. Whenever flow stopped before the viscometer was completely empty (due to uneven packing) the recording was discarded; similarly the first recording for any meal was discarded also because it was often the highest due, possibly, to particles of the previous meal adhering to the pipe. Recordings for each meal were continued until five consecutive readings were of the same order. The meal emptied from the viscometer was weighed and the apparent density determined from this weight and the volume of the viscometer. The meal moisture contents were kept constant throughout the experiments by continual checking with a Marconi moisture meter.

Calibration of the viscometer was carried out with water at different temperatures because the viscosity of water varied with temperature according to Jameson's[56] Tables. The time for a constant volume of water to flow through the viscometer was recorded for each temperature and by plotting time (t seconds) against the known water viscosity at each temperature a correction factor was obtained. Evans[57] expressed kinematic viscosity, u_k, as follows -

$$u_k = k + \frac{c}{t}$$

where k and c were calibrated constants to be evaluated graphically.

From the results in Appendix A10 the calibration equation for the standard or small viscometer was -

$$u_k = 1.79t - 0.91 \text{ cm}^2/\text{sec}$$

A large viscometer had to be constructed to obtain values for the viscosity of coarse-grained meals, such as flaked wheat and maize, crushed oats and dried grass meal, because they would not flow in the small viscometer. The large model had the same length but its bore was increased to 28 mm with a subsequent increase in volume to 1870 ml. It was calibrated by the method described above to give the following equation -

$$u_k = 0.23 + 0.45t \quad \text{cm}^2/\text{sec}$$

To confirm the validity of these equations tests were carried out with ground barley, wheat, milo and beans under the same conditions of fineness and moisture content for both viscometers. The times for flow in each case were converted to kinematic viscosity using the relevant calibration equations and the results in the table below show excellent correlation between the two pipes.

TABLE 7.

Meal	Small viscometer		Large Viscometer	
	t sec	u_k cm^2/sec	t sec	u_k cm^2/sec
$\frac{1}{8}$" ground wheat	1.8	2.30	4.6	2.30
$\frac{1}{8}$" ground milo	1.6	1.95	3.5	1.81
3/16" ground barley	3.7	5.71	10.8	5.09
$\frac{1}{4}$" ground beans	2.6	3.74	7.8	3.74

Testing the significance of these two sets of values for kinematic viscosity showed a good correlation with a value for probability of 0.95 for the differences. It was concluded that the kinematic viscosity of meals could be measured accurately with a pipe viscometer of the type described in this Section provided that it was calibrated with fluids of known viscosity. Photographs of the viscometer are shown in Fig.16.

4.10 The effect of moisture content on the viscosity of meals.

Increases in moisture content increased the stickiness of particles and hence their adherence to one another, consequently, this reduction in freedom to move throughout the mix reduced the chance of interfacial exchange between particles and mixing would become less efficient.

Moisture content played an additional part in the behaviour of meals because of their organic nature and the existence of osmosis between cells composing the particles. In this way water was more readily absorbed by true meals than powders or minerals and so a higher moisture content was

possible before the same retardation of flow became apparent. No details of past work on the effect of moisture content of meals was available, however, it had been observed that higher moisture contents caused bridging in bulked meals, followed by overheating and deterioration in the more extreme cases. Silver[14] discovered that the rate of output when grinding cereals decreased as a power of increases in moisture content.

The effect of moisture content of a meal on its viscosity was investigated with the standard small pipe viscometer in order to obtain a value of kinematic viscosity for each moisture content. Samples of wheat and barley meals were tested. The first test in each case was performed on a sample of meal of normal moisture content, i.e. atmospheric conditions, and then its moisture content was either reduced by oven drying or increased by steaming. The procedure for steaming a meal consisted of sieving it and then reversing the sieve order before placing the nest, less the pan, over a steam chamber. Steaming was discontinued before condensation could occur and the sieve fractions remixed before testing the moisture content with a Marconi meter. The range of moisture contents was increased by thoroughly mixing steamed and unsteamed meals in various proportions.

The results were examined by plotting graphically the moisture content against the time of flow in the viscometer for each meal.

4.11 The examination of porosity and bulkiness of meals.

The discourse in section 2.14 et seq. showed that porosity was the percentage of voids, V, in a packing and that it could be measured once the true and apparent densities were known. The degree of packing depended on particle shape and the amount of voids, consequently any two meals of similar true density, p, and porosity would have different packing bulkiness if their particle size and shape characteristics were dissimilar.

$$\text{Porosity} = 100 \times V$$

$$= 100 \times p_a\left(\frac{1}{p_a} - \frac{1}{p}\right)$$

$$\text{Bulkiness} = \frac{1}{p_a}$$

The true density of a meal was obtained by the water displacement method using the whole grains of the material that were ground to produce the meal. The chance of absorbing moisture was examined by accurate weighing before and after and was considered to be slight being counterbalanced by very small air bubbles that were not dispersed entirely by stirring. The apparent density was the density of the meal packing in the viscometer as mentioned previously. Values for porosity and bulkiness were calculated from the results of the density tests.

INVESTIGATION OF THE MIXER DESIGN FACTORS.

4.12 The design and construction of the model mixer.

In order to examine the factors of design that affect mixing in vertical auger-type mixers it was necessary to build an experimental mixer in which each design feature would be independent by variable. The cost and the amount of meal needed for each mix precluded the construction of a full-size mixer and so it was necessary to design a model; the mixer installed in the foodstore on the Edinburgh School of Agriculture farm was a Reffold bottom-feed vertical-type with a capacity of 10 cwt and in order to draw a comparison, it was decided to base the model on it. A half-scale model was chosen for convenience of size and calibration and its design variables constructed to allow it to be adjusted to represent a scale replica of the full-size machine shown in Fig.18.

The factors affecting the scaling-down of a mixer are twofold, those that affect dimensions of the machine and those that affect the flow of the meals. The former presented little difficulty as they were scaled-down according to the size ratio, but the latter were more involved because flow depended on the constants R and F. (see section 2.17). These constants must be identical for the model and the full-size mixer, but they were both functions of velocity which was also a function of the mixer dimensions, consequently, the factors were complicated by this inter-relationship.

$$\text{Reynolds No. } R = \frac{pLv}{u}$$

$$\text{Froude No. } F = \frac{v^2}{gL}$$

$$\text{Time factor} = \frac{vt}{L}$$

In the model the length dimension, L, was reduced and so the velocity, v, of the model had to be increased to maintain a constant value for R; however, to keep F constant with a reduced value for L the velocity had to be decreased. This was contradictory and could be solved only by changing density, p, and viscosity, u, of the meals to be used in the model mixer.

Fosset and Prosser[58] showed the value of R to be unimportant when studying the mixing of tetraethyl lead and gasoline in models and the time factor was found to be approximately constant provided that F, referring to the relative movement of light and heavy liquids, exceeded a certain critical value.

Kramers et al.[59] investigated mixing by stirrers in tanks over a range of variables and found that F and R were relatively unimportant and that the time factor was roughly constant for an arbitarily defined degree of mixing. Similar results were found by Rushton[60] during his extensive experiments on power required by model mixers.

Bearing these previous results in mind it was decided to carry out the initial tests with normal and half-scale meals in order to discover the importance of R and F with reference to meal mixing. The dimensional factors had to be scaled down, in this case to half-size, and the values of the dimensional components for the model are given below:-

$$\text{Linear dimensions of model} = \frac{L}{2} = L_m$$

$$\text{Area dimensions of model} = \frac{L^2}{4} = L_m^2$$

$$\text{Volume dimensions of model} = \frac{L^3}{8} = L_m^3$$

Therefore the model based on the 10 cwt. mixer would have a capacity of

Therefore the model based on the 10 cwt. mixer would have a capacity of 1.25 cwt. The time factor had to be taken into account also and according to previous work it would be constant whilst R would be unimportant, therefore for constant Froude Numbers:-

$$\frac{v^2}{gL} = \frac{v_m^2}{gL_m}$$

Where m was a suffix denoting the model. But $L_m = \frac{L}{2}$ and gravity, g would be constant also

therefore

$$v_m^2 = \frac{v^2}{2}$$

$$v_m = \sqrt{\frac{v^2}{2}} = 0.706v$$

Using those values for the time factor gave a similar result,

$$t_m = 0.706t$$

The examination of half-scale meals showed that they were unsuitable for the purposes of scaling down. When compared with full-scale meals, the mean weight was reduced proportionally and thus upset the scale requirements of the centrifugal force factor. This factor should remain constant for model and full-size mixers.

$$\text{i.e. } \frac{wv^2}{gL_p} = \text{constant}$$

Where w = particle weight and L_p = radius of gyration.

Since it has been shown that $L_m = L/2$ and $v_m = V/\sqrt{2}$ it followed that $w_m = w$.

As a result of those considerations the experiments were conducted in the model with full-scale meals and, provided that mixing proceeded according to the same general equation, the mixing in the model could be related to that in the full-size mixer by means of correction factors. Later this was proved to be the case.

The construction of the model mixer proceeded according to the specifications in the sectioned drawing in Fig.17. The slope angle of the hoppered mixing chamber was 62° to conform with the results of the angle of repose experiments as well as the angle for the full-size mixer to be used as a comparison. The auger was driven by Vee-belt from a general electric motor whose output was 350 r.p.m. and the complete mixer was mounted on a base plate for mobility. The variable design features are listed below:-

1. In-feed position - The bottom-feed version is shown in Fig.19, but the bottom-feed cylinder could be removed from the base of the mixing chamber along with the lower part of the auger to convert the mixer into a top-feed version (see Fig.20). In the top-feed version the auger base was closed by a cover-plate and the mixer was filled by removing one half of the lid; in both versions the discharge point was the same.

2. Auger speed - This was varied by means of a Hainsworth variable speed pulley and a special Fenner belt which gave an infinite range of speeds between 70 and 600 r.p.m. The speed was changed by means of the screw handle in Fig. 21 that altered the belt tension and the speed was measured by a tachometer.

3. Mixing chamber proportions - could be varied by means of its telescopic side walls being adjustable for height in 3 in. steps. The chamber height could be varied from 12 in. to 24 in., but the diameter remained constant at 22 in. The upper part of the auger could be removed in 3 in. sections to conform to its pitch and this controlled the steps for the height adjustment.

4. Auger shroud - this was shown in place in Fig.17, but it could be removed easily in order to investigate its effect on the mixing of meals. The shroud was held internally by three radial stays.

5. Spreading blades - could be fitted to the upper section of the auger to increase the radial dispersion of the meals.

6. Auger type - the auger fitted initially in the model was a plain edged one having a diameter of 5 in. and a pitch of 3 in.; later it was planned to fit augers with different pitches or notched edge.

1/8th scale

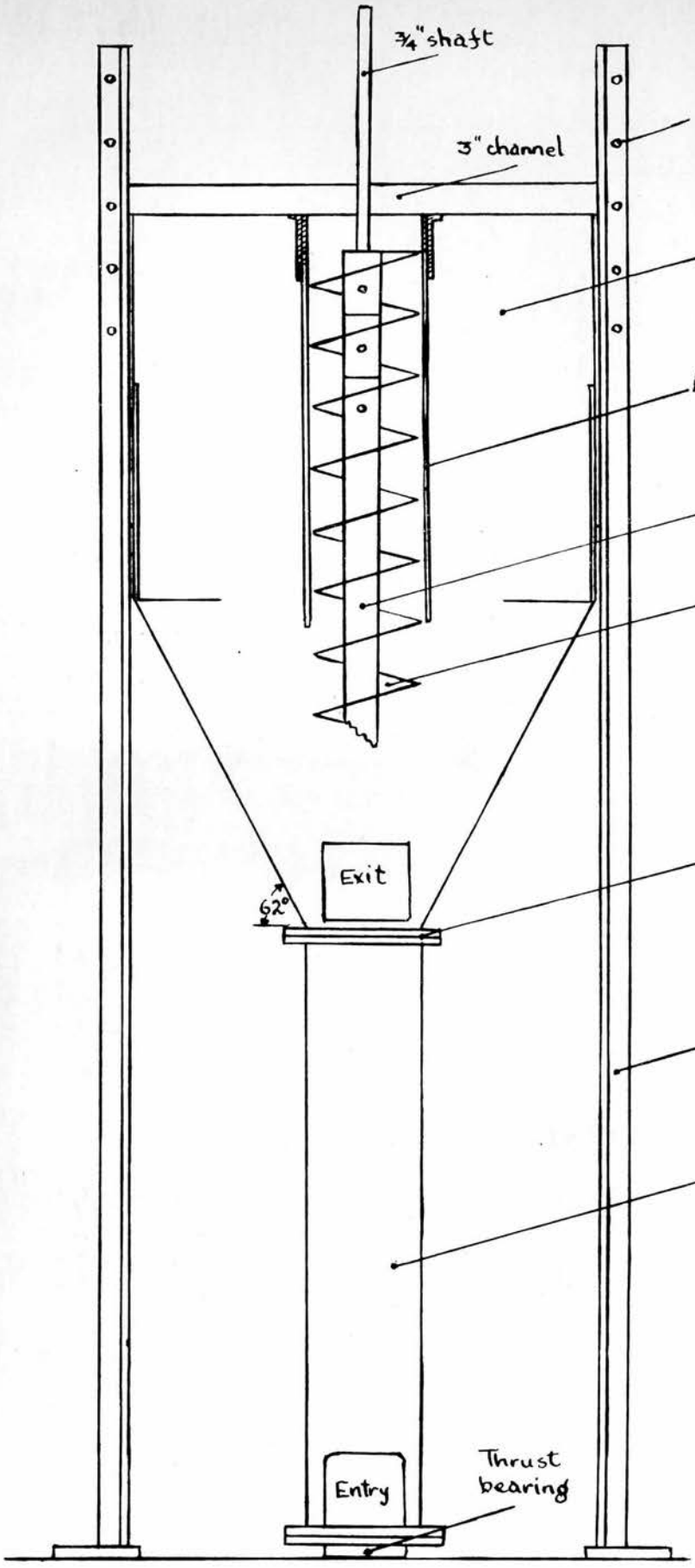


FIG. 13.

SECTIONAL DRAWING OF MODEL MIXER

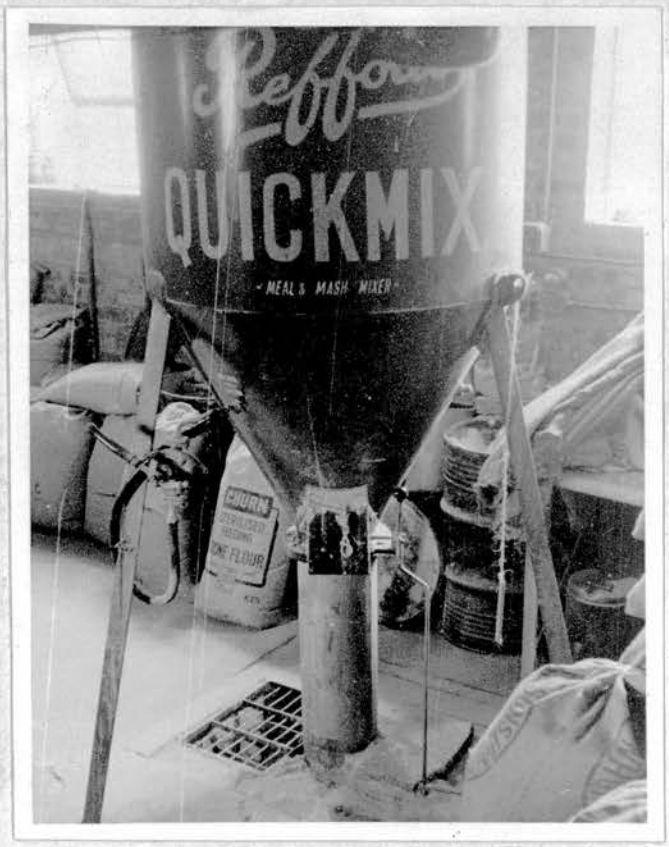


FIG. 18 The Full-size Mixer.

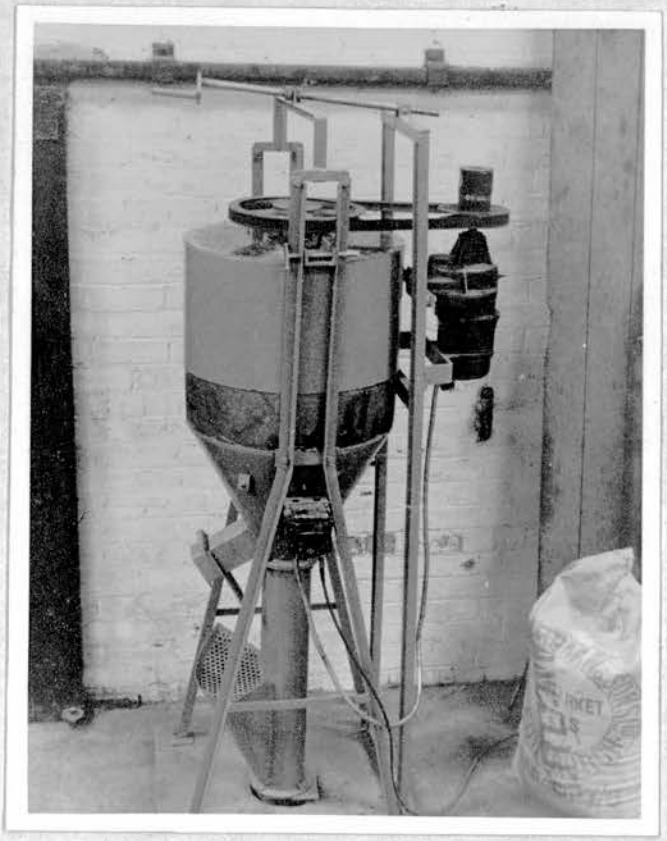


Fig. 19 Model Mixer - bottom feed

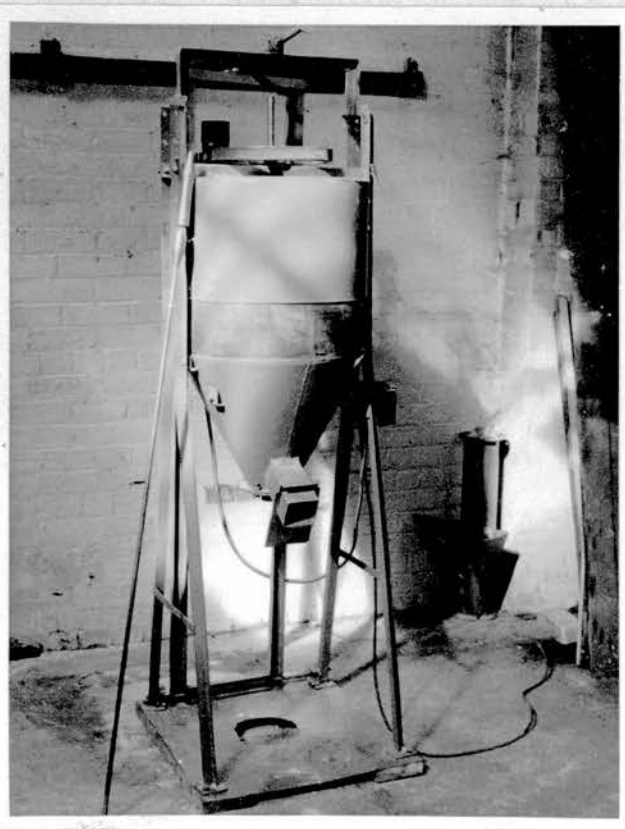


Fig. 20 Model Mixer - top feed

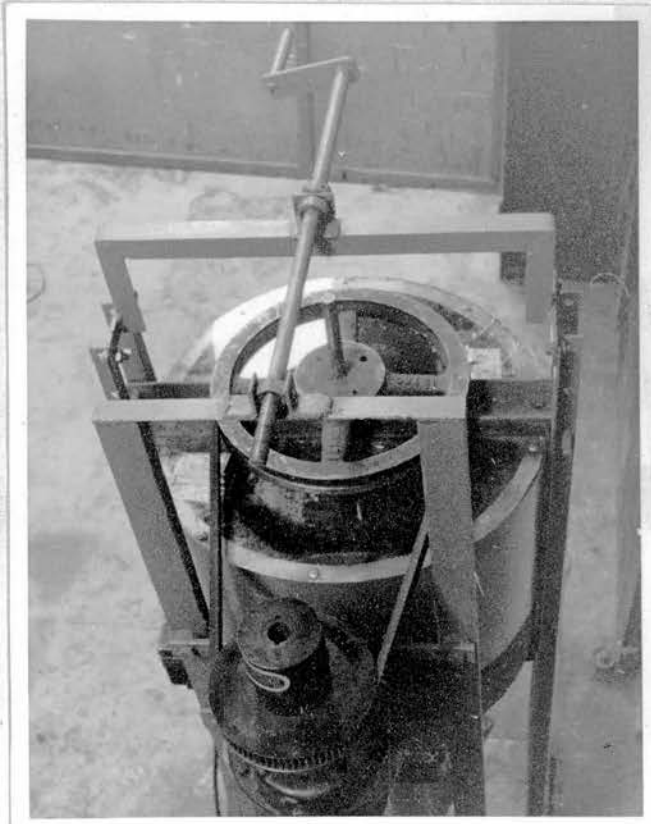


Fig. 21 The Variable Speed Drive

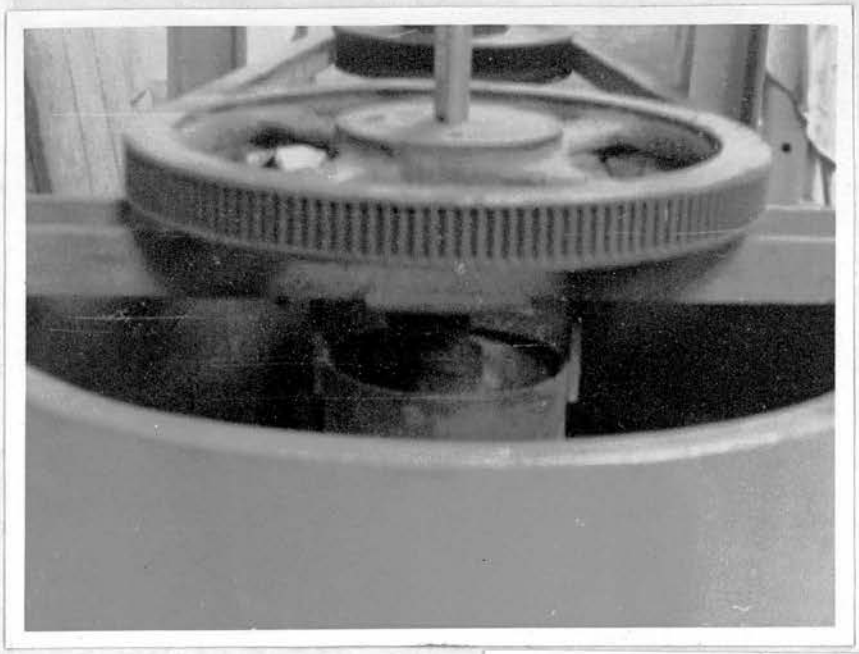


Fig. 22a

The auger drive shaft and pulley on the model mixer; also shown is the cylindrical shroud around the auger.

Fig. 22b

The model mixer in operation mixing salt and barley meal with an auger speed of 190 r.p.m.

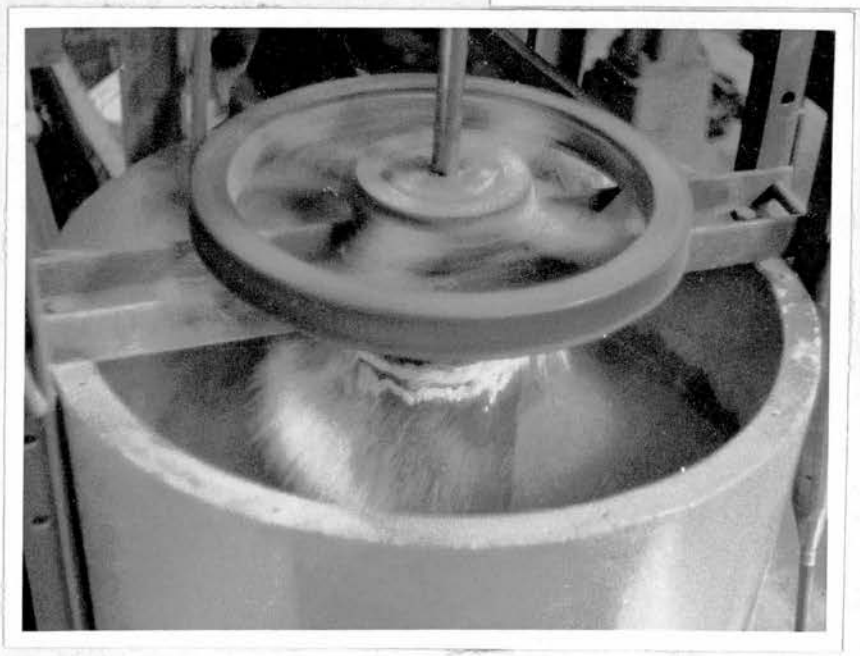


Fig. 22c

The model mixer mixing salt and barley meal at an auger speed of 350 r.p.m. Note the centrifugal separation of the particles.

The mixing chamber lid was made of perspex to allow for observation of the mixing progress, see Fig.22, the bottom-feed hopper was protected by a screen and the auger could be emptied completely by means of a small door in its basal cover-plate. The discharge spout had a specially designed shutter that prevented blockages and meal leakages, whilst its eliptical-shaped aperture gave a precise control of the rate of emptying. The meals were filled into sacks immediately after discharge and the whole mixer cleaned out before the next test was performed.

With many mixers dust control was a serious problem and the model mixer was no exception, however, a simple and effective method of precluding dust was the fitting of a cloth filter over an aperture in the lid. In this way the air induced by the auger at the in-feed position did not increase the internal pressure but was allowed to escape without taking any meal dust with it. One half of the perspex lid was removed in Fig.22 to show the dispersion of the meal from the top of the auger during operation.

The comparison of the model mixer with the full-size one was performed with two radically different binary mixes, namely a 50/50 mix of ground barley meal and dried grass meal and a 1/99 mix of butter salt and ground barley meal. In the first case the dried grass meal was added first and timing started once the whole batch had been fed completely into the mixer. The machines were stopped each time the mix was sampled, the sampling spear was pushed into the mix from above, after removing the lid, and five random samples withdrawn each time. Each mixer was filled to approx. 90% of its capacity, i.e. 448 lb. of each ingredient for the full-size mixer and 56 lb. of each for the model. The sizes of sample for chemical analysis of the dried grass content were 32 gm. and 4 gm. respectively to maintain a similar scale of scrutiny. Each sample was extracted with hot acetone, instead of petrol ether, by a slightly improved technique to that used in the preliminary tests. After extraction the chlorophyll solution was diluted until its wavelength corresponded to the

most accurate absorptiometer recording range and the amount of dried grass present determined from the calibration graph in Appendi x A.11, where the detailed procedure is recorded.

In the case of the salt and barley meal mix half the salt was added with the first barley fed into the hopper and the rest with the last barley charge. The same total weight of mix was used comprisive 887 lb barley meal and 9 lb salt in the full-size mixer and 111 lb barley meal and 1 lb salt in the model. Again five samples were taken with the sampling spear at each time, the sub-sample size for analysis being 240 gm. and 30 gm. respectively to ensure the inclusion of a measurable amount of soluble chloride. The chloride estimation was used to obtain the weight of salt in each sample according to the procedure described in Appendix A.4.

The range of times for sampling was 2 mins to 35 mins in the model mixer and 2.8 mins. to 49.5 mins. in the full-size mixer according to the scale equation, $t_m = 0.706t$; and the auger speeds were 278 r.p.m. and 195 r.p.m. respectively according to the scale equation $v_m = 0.706v$. The model and full-size mixers were identical in all respects except size and in-feed hopper, the full-size mixer having a worm-assisted feed and the model gravity only. Details of the two mixers can be seen in Figs. 18 and 19.

From the results the graphs for time of mixing against the uniformity index of the mix were plotted for each mixer and the resultant curves compared.

4.13 <u>The effect of time on the uniformity of mixing</u>.

Following the experiments that showed that the model mixer was suitable for investigating the mixing of animal feeding stuffs, further experiments were performed to study the effect of the time of mixing on the uniformity of a 20/80 mix of skimmed milk powder and ground barley meal. The milk powder was added first into the bottom-feed version of the model mixer using the shrouded auger at a speed of 190 r.p.m.; five samples were withdrawn by the sampling spear at intervals of time up to 30 minutes and analysed for starch content by the Iodine Blue method (see Appendix A.5) and for crude fibre content by the

Normal Acid Fibre method (see Appendix A.8).

The 18 in. deep mixing chamber was filled to 88% of its capacity with a 112 lb mix consisting of 22 lb milk powder and 90 lb barley meal and the size of sub-sample for each analysis was 4 gm. The uniformity of mixing graph was obtained by plotting time against the corresponding Uniformity Index and compared with the graphs for the mixes of dried grass and barley meal and butter salt and barley meal.

4.14 The effect of the in-feed position to the mixer.

The data obtained with the bottom-feed version of the model mixer was compared, under the same conditions, with the top-feed version. The lower auger section and bottom-feed cylinder were removed and the mixing chamber closed by the base plate in which was incorporated the lower thrust bearing for the auger drive shaft. The milk powder and barley meal were tipped into the top of the mixer in that order directly from sacks, when filling was complete the half lid was replaced and mixing commenced. Samples were withdrawn at the same times as before to ensure a direct comparison.

This experiment was then repeated for a mix composed of 90 lb. ground barley meal and 10 lb dried grass meal using first the top-feed version and then the bottom-feed version of the mixer whilst all other factors remained constant. The standard analyses were made to assess the uniformity index which was compared for both in-feed positions and for the two mixes. After completing the discharge from the mixing chamber outlet the amounts of meal remaining in the mixer varied between 4 and 5 lb with the bottom-feed version and between 3 and 4 oz. with the top-feed version; the larger amount being due to the inability of the lower auger to elevate all the meal from its foot to the discharge point.

4.15 The effect of the auger speed on mixing meals.

The previous experiments were performed at one auger speed, i.e. approximately 190 r.p.m. (the figure varied slightly being preset before mixing commenced and not altered afterwards for fear of altering the mixing process),

whilst the mix was sampled at different time intervals. In this investigation the length of time that mixing occurred was constant but the auger speed was changed for each test.

The model mixer was used in its top-feed version and the auger speed was altered by altering the tension on the belt from the Hainsworth variable speed pulley unit attached to the electric motor drive shaft. This pulley consisted of two separate spring-loaded sheaves; increasing the belt tension, by moving the motor frame away from the mixing chamber caused the sheaves to open and allow the Vee-belt to move in towards the centre of the pulley. In this way the effective pulley diameter was reduced and the belt speed was reduced accordingly. Moving the motor frame towards the mixing chamber reduced the belt tension to below that of the sheave springs tension, this caused the pulley to close and force the belt towards its outside edge with a subsequent increase in speed. The pulley unit had a speed reduction range of 1 to 0.26 times the motor speed of 350 r.p.m., however, the speed could be increased over a similar range by fitting a smaller pulley to the auger shaft. The motor frame was pivoted on the mixer baseplate and it was moved by a screw-handle between it and the topmost mixer support, whilst the auger speed was measured with a tachometer during the mixing process.

Two mixes were used, both of 112 lb total weight, firstly 20/80 milk powder and barley meal and secondly 1/99 salt and barley. Samples were withdrawn after 10 mins. and 20 mins. mixing of the first mix and after 20 mins. mixing of the second and analysed by the Iodine Blue and Soluble Chloride tests respectively. The auger speeds were set for 85, 150, 190, 265, 350 r.p.m. for each mix so that results could be expressed in terms of auger speed and mix uniformity after a certain duration of mixing.

4.16 The effect of different mixing chamber size.

As explained previously the height of the mixing chamber could be altered in 3 in. stages whilst the diameter remained constant at 22 in. This was possible by making the mixing chamber in two sections, the upper section

sliding over the lower one. The gap between the walls was sealed by a ring of rubber-covered flexible cable to prevent dust extrusion. The method of raising and lowering the upper chamber section should be apparent in Fig.19 which shows the mixing chamber in the 18 in. position. Other heights were 12, 15, 21 and 24 in. The auger length was adjusted to suit the mixing chamber size by adding or subtracting 3 in. sections which were pinned to the driving shaft.

The width to depth ratio of the chamber varied from 1.83 to 0.92 and the volume increased from 2.64 cu.ft. to 5.28 cu.ft. over this range. Each test was performed with a 20/80 mix of milk powder and barley meal which was sampled after 20 mins. using the normal procedure. The meals were fed through the top of the mixer and mixed with the shrouded auger at a speed of 190 r.p.m. for a period of 20 mins. The results were used to examine the possibility of the mixing chamber size being a function of the uniformity of mixing.

4.17 The effect of shrouding the mixing auger.

A cylindrical shroud was fitted to the model mixer so that it would resemble the full-size mixer and it remained in position for all the subsequent experiments, however, to investigate its effect on the uniformity of mixing it was necessary to carry out a test with it removed. The mix used was composed of 20% milk powder and 80% barley meal. They were mixed at 190 r.p.m. in the top-feed version of the mixer with an 18 in. mixing chamber height and samples were withdrawn after, 10, 20 and 30 mins. mixing.

The test run was identical to the one in section 4.13 except for the removal of the shroud, consequently the two tests were used to examine the effect of the auger shroud on the uniformity of mixing.

4.18 The effect of fitting spreading blades to the auger.

Some vertical auger mixers were fitted with two or more blades at the top of the auger to increase the radial dispersion of the meals during mixing. Spreading blades were not fitted during the previous tests so two were fitted to investigate their effect; each was one inch deep and two inches long and welded

to a collar diametrically opposite one another. The collar was then slipped over the auger drive shaft (after removing the mixer lid) and clamped in position immediately above the auger with the blades in line with the auger's trailing edge. The spreading blades rotated at the same speed as the auger, 190 r.p.m., inside the diameter of the shroud which was fitted still.

The test was carried out with a 20/80 mix of milk powder and barley meal in the top-feed version of the model mixer and the results composed with those obtained from the test described in section 4.13 when the spreading blades were not fitted.

4.19 The effect of different types of auger on the mixing process.

There was insufficient time during this study to construct and examine other types of mixing auger. The effect of altering the auger pitch would be to increase or decrease the rate of mixing but it was unlikely that it would alter the over-all degree of uniformity. Very few machines fitted augers other than the plain type used in these experiments, but there was a possibility that a wavy-edged or notched auger would increase the amount of agitation imparted to the meals.

INVESTIGATION OF THE MIX COMPOSITION.

4.20 The effect of component proportions on the uniformity of mixing.

This experiment was carried out with a mixture of dried grass meal and ground barley meal, the barley formed the bulk of the mix whilst the proportion of dried grass was varied. The proportions of dried grass examined were 0.5, 0.25, 0.1 and 0.05.

The total weight of mix each time was 112 lb., but, due to the smaller apparent density of the dried grass the volume diminished with decreasing proportions of dried grass in the mix. The dried grass was added first in each test in the bottom-feed version of the model mixer and mixed with the shrouded auger at a speed of 190 r.p.m. In the first test samples were withdrawn with the sampling spear at five minute intervals up to a total mixing time of 30 mins. in order to establish the form of the mixing curve, in the subsequent tests samples were withdrawn at ten minute intervals. Five samples at each

time were analysed to obtain the dried grass content and the results used to calculate the Uniformity Index.

4.21 The effect of meal viscosity on the uniformity of mixing.

In order to test the effect of the viscosity of meals all other variables had to be eliminated, this was done by using a constant mixing time, the same ingredient proportions and the same mixing process whilst mixing components of different viscosity values. A full range of tests was not carried out at this stage, consequently, the results could give only a general indication of the part played by viscosity when mixing meals.

The bottom-feed mixer version was used and mixes with a 20/80 ingredient proportion were mixed with the shrouded auger at a speed of 190 r.p.m. Five samples were withdrawn after 20 mins. mixing and later analysed. Results were available for 20/80 dried grass and barley meal and 20/80 milk powder and barley meal mixes and so a further test was performed with a 20/80 mix of butter salt and barley to produce enough data to plot a graph of viscosity against Uniformity Index for each combination.

4.22 The effect of the shape and size of meal particles.

No specific tests could be carried out to establish relations between the size or shape of particles and the uniformity of mixing; however, they could be examined indirectly because equations had been determined for specific surface and viscosity, and viscosity and uniformity of mixing.

4.23 The mixing of more than two components.

So far only two components of a mix had been investigated in order to restrict the number of variables that occur during mixing, whilst in practice animal feeding stuffs contain many components. Investigating more than two components required the ability of more than one analysis to be performed on one sample so that the Uniformity Index of each component could be established; from this data the uniformity of the mix, U_z, could be calculated.

The first examination was done on the 20/80 milk powder and barley meal mix used in section 4.12 because the barley meal was analysed for both starch

and fibre content. Microscopic examination had shown that cereal grains when ground seperated into roughly two groups - the starchy particles and the fibrous particles, therefore these two groups could represent two components of a mix. The values of the individual Uniformity Indices and the Uniformity Index of the mix were plotted against time and the graphical result studied.

The second examination was performed with a mix containing 1% butter salt, 10% dried grass meal and 89% ground barley meal which was mixed in the bottom-feed mixer with the shrouded auger at a speed of 192 r.p.m. Five samples were withdrawn at ten minute intervals and later analysed for salt and dried grass content. The results were expressed graphically once again.

A final examination was made of a complete poultry meal; analyses were made of each ingredient and of the complete mix, three samples of which were taken on two occasions after 35 mins. mixing in the full-size Reffold mixer. The meals were analysed for protein, oil, fibre, nitrogen free extracts, mineral matter and moisture content and each expressed as a percentage of the whole. The uniformity of the mix was estimated by comparing the % of each substance that should be present if uniform with the actual % in the samples from the mixer.

4.24 The effect of feeding non-uniform mixes to animals.

The ultimate object of any investigation of the mixing of animal feeding stuffs should be the examination of the effect of feeding non-uniform mixes to different animals; this would constitute another thesis study in itself. However, for the sake of interest, a very simple exploratory trial was carried out on the writer's holding with large white pigs. Ten pigs from a single twelve weeks old litter were divided into two equal groups of approximately the same total weight and fed individually twice daily. One group was fed with a 100% uniform mix and the other group with a mix that was 10% deficient in protein (the maximum amount allowed by the Ministry of Agriculture for animal feeding stuffs), each was produced artifically by weighing the amount of each ingredient in a ration. Only three ingredients were used in the feeding stuffs to simplify their preparation but they were nutritionally balanced.

Ration A

Uniformity Index = 0

70% ground barley meal	: crude protein	= 0.7 x 7.6	=	5.32%
20% skimmed milk powder	: " "	= 0.2 x 34.0	=	6.80%
10% dried grass meal	: " "	= 0.1 x 15.1	=	1.51%
		Total crude protein	=	13.63%

Ration B

Uniformity Index = 0.011

77.6% ground barley meal	: crude protein	= 0.776 x 7.6	=	5.90%
15.7% skimmed milk powder	: " "	= 0.157 x 34.0	=	5.34%
6.7% dried grass meal	: " "	= 0.067 x 15.1	=	1.03%
		Total crude protein	=	12.27%

The pigs were weighed weekly and the trial continued for six weeks after which the results were analysed statistically in order to examine any weight differences that occurred between the two groups. The statistical analysis was based on examples by Saunders and Rayner[62].

It was realised that this experiment had only very limited value because the number of replicates was small, the period of investigation was short and the composition of the ration was not ideal. However it was included in this study for what it was worth to future investigators.

5. THE EXPERIMENTAL RESULTS.

The experimental results are recorded in this chapter in tabulated form and in the sequence outlined in section 4.2. After recording the results of each experiment they are examined briefly, but a general discussion of the results from this study of the mixing of animal feeding stuffs is reserved until chapter 6.

EXAMINATION OF THE PROPERTIES OF MEALS.

5.1 Particle size and shape characters.

TABLE 8.

True densities of meals by water displacement method.

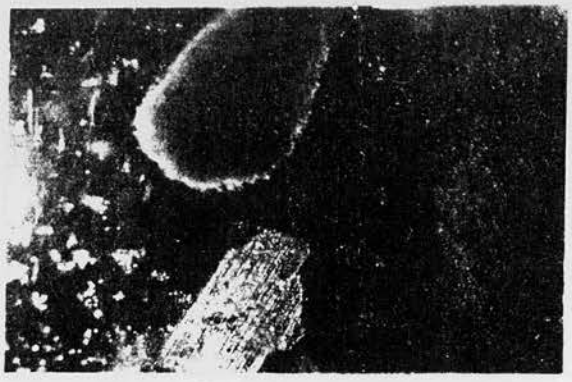
Material	Density gm/ml
Wheat grains	1.22
Barley grains	1.10
Milo grains	1.15
Oat grains	1.00
Maize grains	1.34
Beans	1.40
Dried grass meal	0.89
Fish meals	1.39
Butter salt	2.35
Ground Limestone	2.46
SteamBone Flour	0.98
Skimmed Milk	1.46
Beta No. 10	1.26

TABLE 9.

Particle shape constants and specific surface.

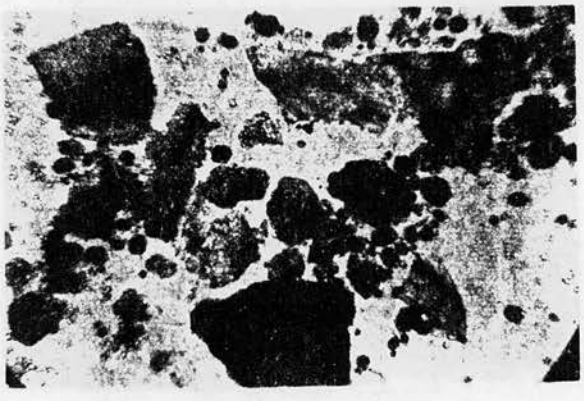
Meal	f	k	d_p Microns	S (cm^2/gm)
¼" ground barley	2.13	0.14	1080	125
3/16" ground barley	1.92	0.13	871	153
⅛" ground barley	1.89	0.12	534	250
3/16" ground milo	1.98	0.13	514	262
3/16" ground oats	2.19	0.16	882	145
Dried grass meal	2.67	0.23	193	587
Ground Limestone	2.02	0.12	48	791
Butter salt	3.08	0.29	417	211
Skimmed milk	2.00	0.12	282	415

MICROSCOPE PHOTOGRAPHS OF MEAL PARTICLES.



GROUND BARLEY x 80.

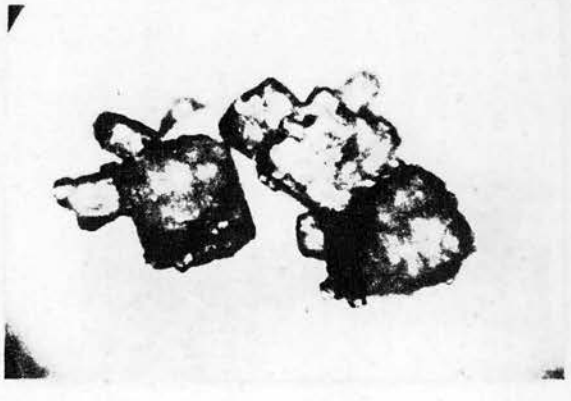
GROUND OATS x 80.



GROUND MILO x 140.

DRIED GRASS MEAL x 140.

SKIMMED MILK POWDER x 140.



BUTTER SALT x 140.

The densities of the cereal meals were all close to unity and it was only the ground limestone and salt that differed greatly from the rest. The values for the shape constants f and k varied considerably from those quoted for mineral materials by Heywood[6]. The values for meals were approximately 2.0 and 0.13 respectively and the ratio h/η was generally around 3/1 as shown in Appendix A.13.

Looking at Table 9 there appeared to be marked fluctuations between corresponding values of S and dp, but plotting them as a graph in Fig. 23 produced a definite hyperbolic curve, which gave the following relationship after rectifications in Appendix A.13-

$$S = 900\, dp^{0.87}$$

There was a direct relationship between S and the reciprocal of d_p for the different sizes of ground barley which proved that the equation derived in section 2.9 held good. (see graph in Appendix A.13).

5.2 The Fineness and Uniformity Moduli.

The value of the length mean diameter, d_l, for each meal was calculated from the equation derived in section 2.13.

$$d_l = 105\,(2)^{F.M.}$$

its value is expressed in microns.

The values for the Fineness and Uniformity Moduli were obtained from the particle size analysis by sieving. The mean % sieve fractions and values for d_l, F.M. and U.M. are classified according to meal type, in tables 10, 11, 12 and 13 on the succeeding pages. The induvidual wts. of the sieve fractions will be found in Appendix A.14.

TABLE 10

Particle Size Analysis of Cereal Meals.

MEAL	Sieve Fraction (%) 4	8	16	30	50	100	Pan	d_1	F.M	U.M.
½" Ground Barley	-	10.5	43.6	26.4	10.5	4.4	4.6	1044	3.31	1:7:2
3/16" Ground Barley	-	2.1	38.3	33.5	15.2	6.2	4.7	841	3.01	0:7:3
⅛" Ground Barley	-	-	13.8	42.5	25.0	10.3	8.4	518	2.33	O:6:4
1/16" Ground Barley	-	-	3.2	19.7	38.8	22.5	18.8	346	1.72	0:2:8
Crushed Oats	17.1	59.7	15.4	4.5	1.0	1.0	1.3	2905	4.79	8:2:0
¼" Ground Oats	-	6.1	48.6	25.0	8.2	9.0	3.1	1003	3.26	1:7:2
3/16" Ground Oats	-	1.4	39.9	31.6	15.3	9.7	2.1	857	3.03	0:7:3
⅛" Ground Oats	-	-	11.0	41.4	22.7	21.6	3.3	529	2.35	0:5:5
1/16" Ground Oats	-	-	1.2	20.1	34.8	39.3	4.6	355	1.76	0:2:8
Flaked Wheat	16.7	48.5	26.8	6.8	0.9	0.3	-	2770	4.72	7:3:0
Broad Wheat Bran	-	17.8	43.0	28.7	6.6	1.5	3.4	1291	3.62	2:7:1
Fine Wheat Bran	-	-	-	0.2	35.1	51.5	13.2	245	1.22	0:0:10
¼" Ground Wheat	-	6.6	38.3	22.6	14.5	11.8	6.2	811	2.95	1:6:3
3/16" Ground Wheat	-	1.7	32.5	27.4	18.4	11.4	8.6	675	2.69	0:6:4
⅛" Ground Wheat	-	0.5	15.1	29.4	22.6	18.4	14.0	466	2.15	0:4:6
1/16" Ground Wheat	-	-	2.8	18.3	29.1	25.8	24.0	297	1.50	0:2:8
Flaked Maize	46.9	34.9	10.6	4.5	1.4	1.1	0.6	3740	5.16	8:2:0
1/16" Ground Maize	-	-	-	16.1	61.5	22.1	0.3	374	1.83	O:2:8
¼" Ground Milo	-	0.8	16.1	45.6	22.3	14.5	0.9	655	2.64	0:6:4
3/16" Ground Milo	-	0.3	7.9	42.9	26.8	20.3	3.5	539	2.36	0:5:5
⅛" Ground Milo	-	-	3.8	31.7	34.9	13.9	15.7	432	2.04	0:4:6
1/16" Ground Milo	-	-	0.9	15.1	30.0	20.1	33.9	257	1.29	O:2:8

TABLE 11

Particle Size Analysis of Non-Cereal Vegetable Meals.

MEAL	Sieve Fraction (%) 4	8	16	30	50	100	Pan	d_1	F.M.	U.M.
¼" Ground Beans	0.9	11.2	39.3	24.5	11.6	6.1	6.4	971	3.21	1:6:3
3/16" Ground Beans	-	2.6	29.8	28.5	16.4	9.5	14.2	638	2.60	0:6:4
⅛" Ground Beans	-	0.1	8.2	34.8	24.3	13.2	19.4	420	2.00	0:4:6
1/16" Ground Beans	-	-	1.2	12.3	20.1	20.1	46.3	213	1.02	0:1:9
Soyabean Meal	-	-	14.6	44.7	26.7	9.9	4.1	618	2.56	0:6:4
Groundnut Meal	-	1.1	3.9	12.7	40.4	40.1	1.8	356	1.80	0:2:8
Dried Grass meal	-	-	-	1.3	19.5	48.4	30.8	188	1.91	0:0:10

TABLE 12.

Particle Size Analysis of Animal Meals

MEAL	Sieve Fraction (%)									
	4	8	16	30	50	100	Pan	d_1	F.M.	U.M.
White Fish Meal	-	-	3.9	14.3	19.8	33.5	28.5	263	1.32	0:2:8
Meat and Bone Meal	-	3.1	24.0	25.7	39.8	7.3	0.1	713	2.76	0:5:5
Steam Bone Flour	-	-	-	4.1	10.6	19.4	65.9	151	0.53	0:0:10
Milk Powder	-	-	0.2	6.3	42.6	32.7	18.2	173	1.38	0:1:9
Whey Powder	-	-	0.4	6.9	23.2	28.1	41.4	206	0.97	0:1:9

Moisture contents were kept constant at 14% for the home-produced meals and 10% for the bought-in meals.

d_1 was measured in microns.

TABLE 13.

Particle Size Analysis of Minerals and Supplements.

MEAL	Sieve Fraction (%)									
	4	8	16	30	50	100	Pan	d_1	F.M.	U.M.
Ground Limestone	-	-	-	0.1	0.2	14.9	84.8	32	0.16	0:0:10
Dairy Minerals	-	-	-	1.7	2.4	34.9	61.1	143	0.44	0:0:10
Beta No. 8	-	-	-	11.9	42.0	23.7	22.4	282	1.43	0:1:9
Beta No.10	-	-	-	13.4	37.1	22.2	27.3	271	1.37	0:1:9
Beta No.16	-	-	0.4	11.4	39.6	33.4	15.2	293	1.48	0:1:9
Molassine Meal	7.7	14.5	33.9	40.0	3.8	0.1	-	1470	3.80	2:7:1
Butter Salt	-	-	-	3.0	90.4	6.6	-	408	1.96	0:0:10

The values of the Fineness Modulus, F.M. varied between 5.16 for the coarsest meal to 0.16 for the finest, flaked maize and ground limestone respectively, whilst the Uniformity Modulus, U.M., could differentiate between meals with the same F.M., e.g. $\frac{1}{8}$" ground oats and $\frac{1}{8}$" ground barley meals. Alternatively meals with the same U.M. generally had a different F.M., e.g. wheat bran, dried grass meal and ground limestone.

Many meals were composed of medium and fine particles and some fine

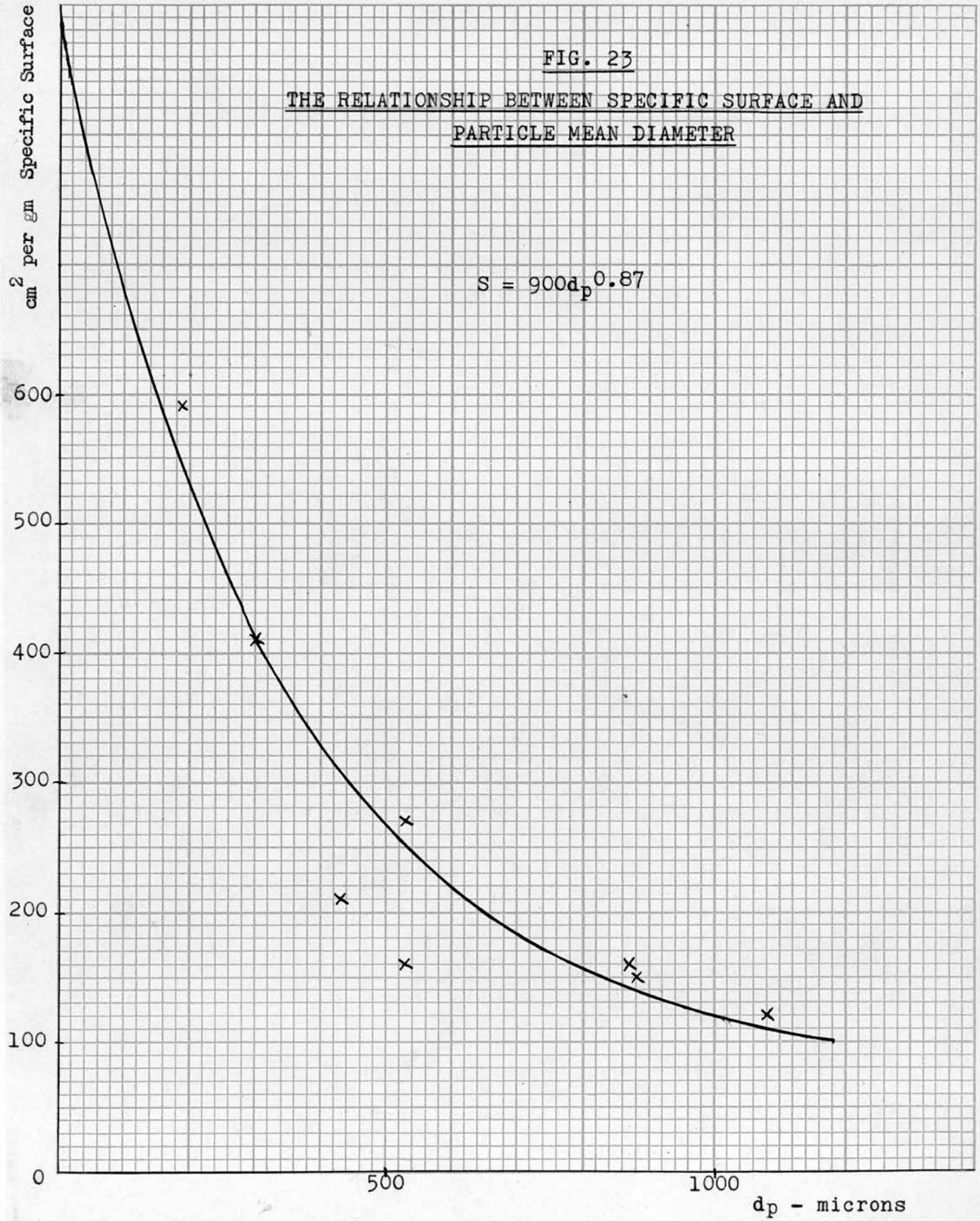


FIG. 23
THE RELATIONSHIP BETWEEN SPECIFIC SURFACE AND PARTICLE MEAN DIAMETER
$S = 900 d_p^{0.87}$
Specific Surface
cm^2 per gm
600
500
400
300
200
100
0
500
1000
d_p - microns

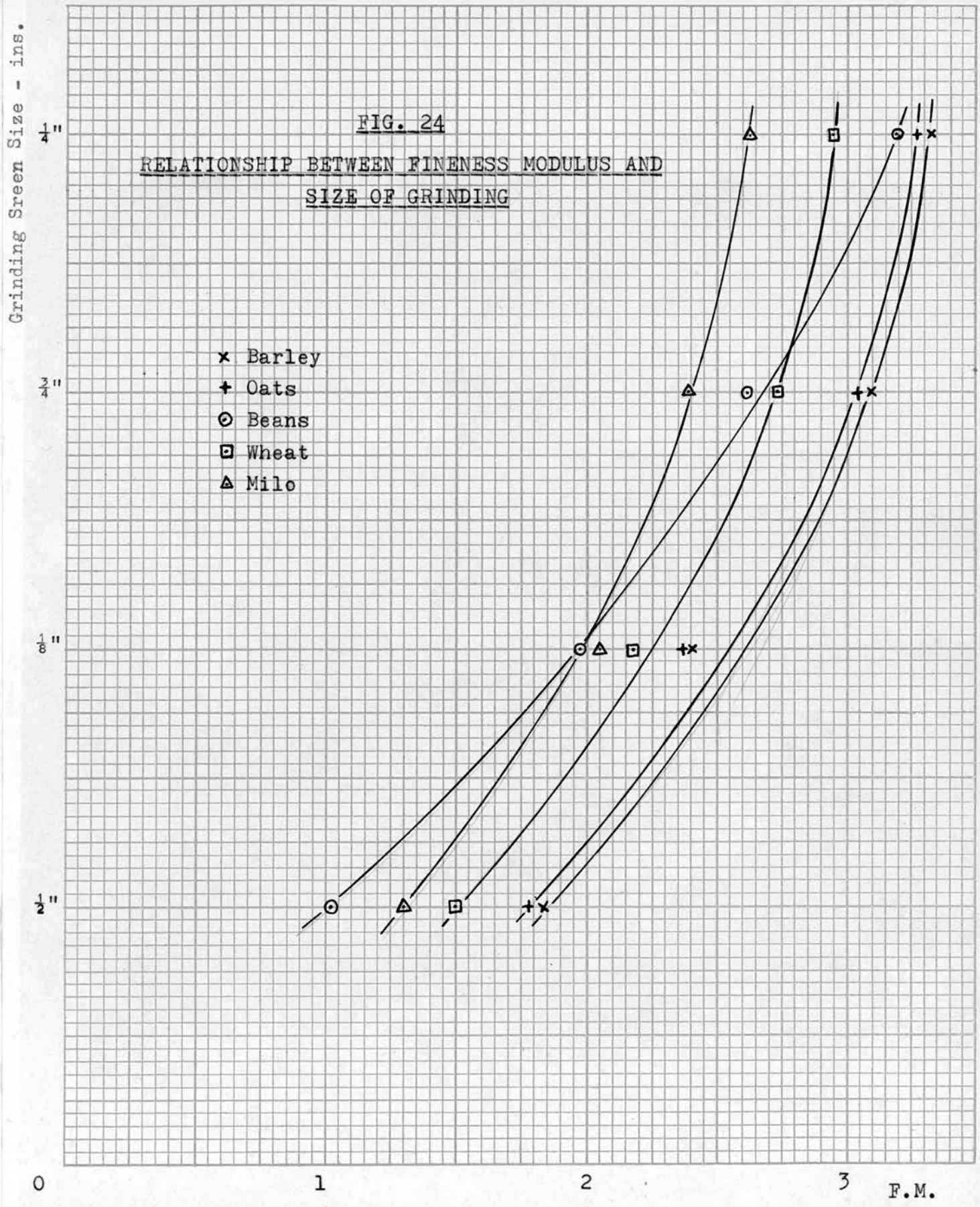


FIG. 24
RELATIONSHIP BETWEEN FINENESS MODULUS AND SIZE OF GRINDING
Grinding Sreen Size - ins.
¼"
⅜"
⅛"
½"
Barley
Oats
Beans
Wheat
Milo
0
1
2
3
F.M.

FIG. 25

THE EFFECT OF THE SIZE OF GRINDING ON THE SPECIFIC SURFACE OF BARLEY MEAL

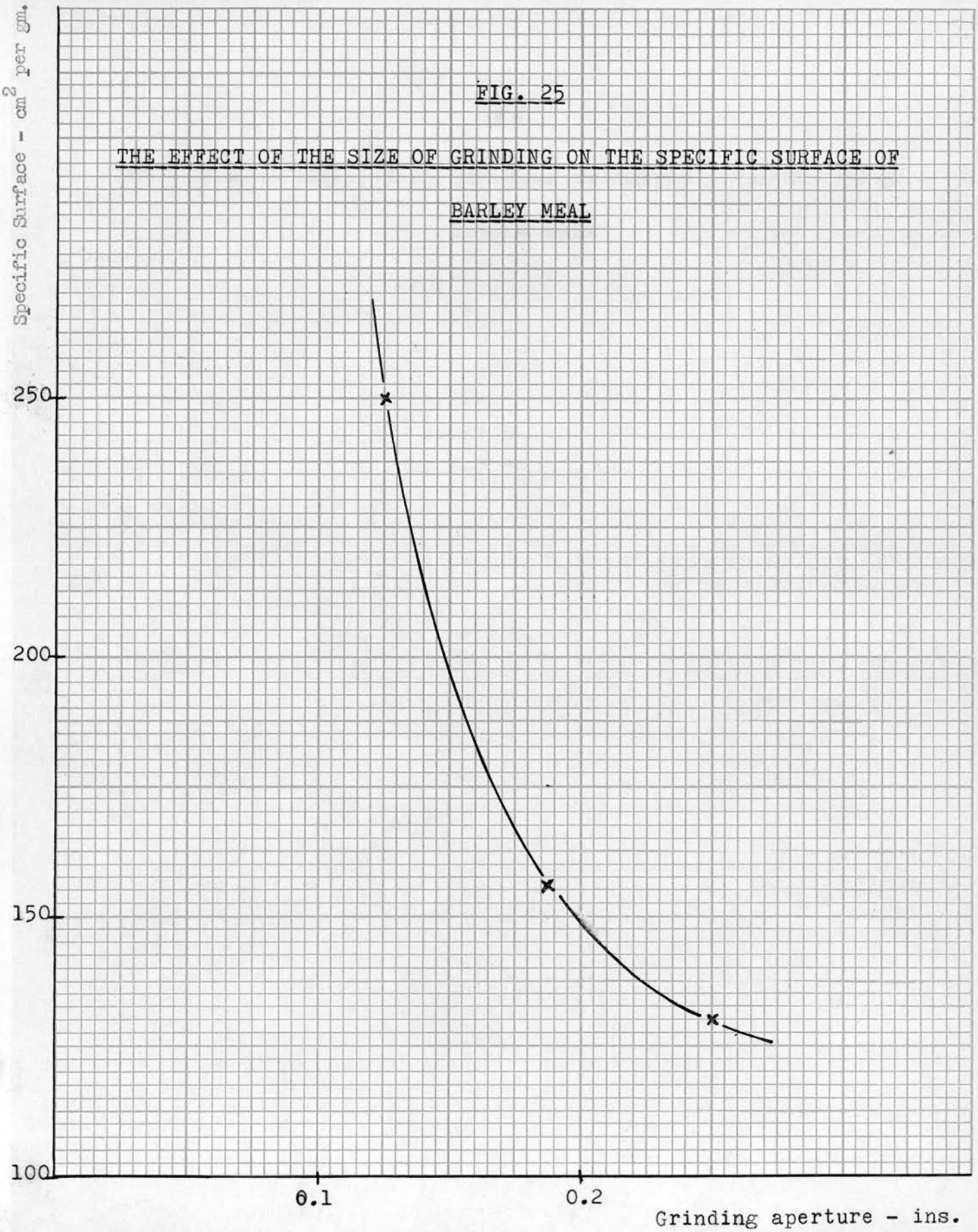
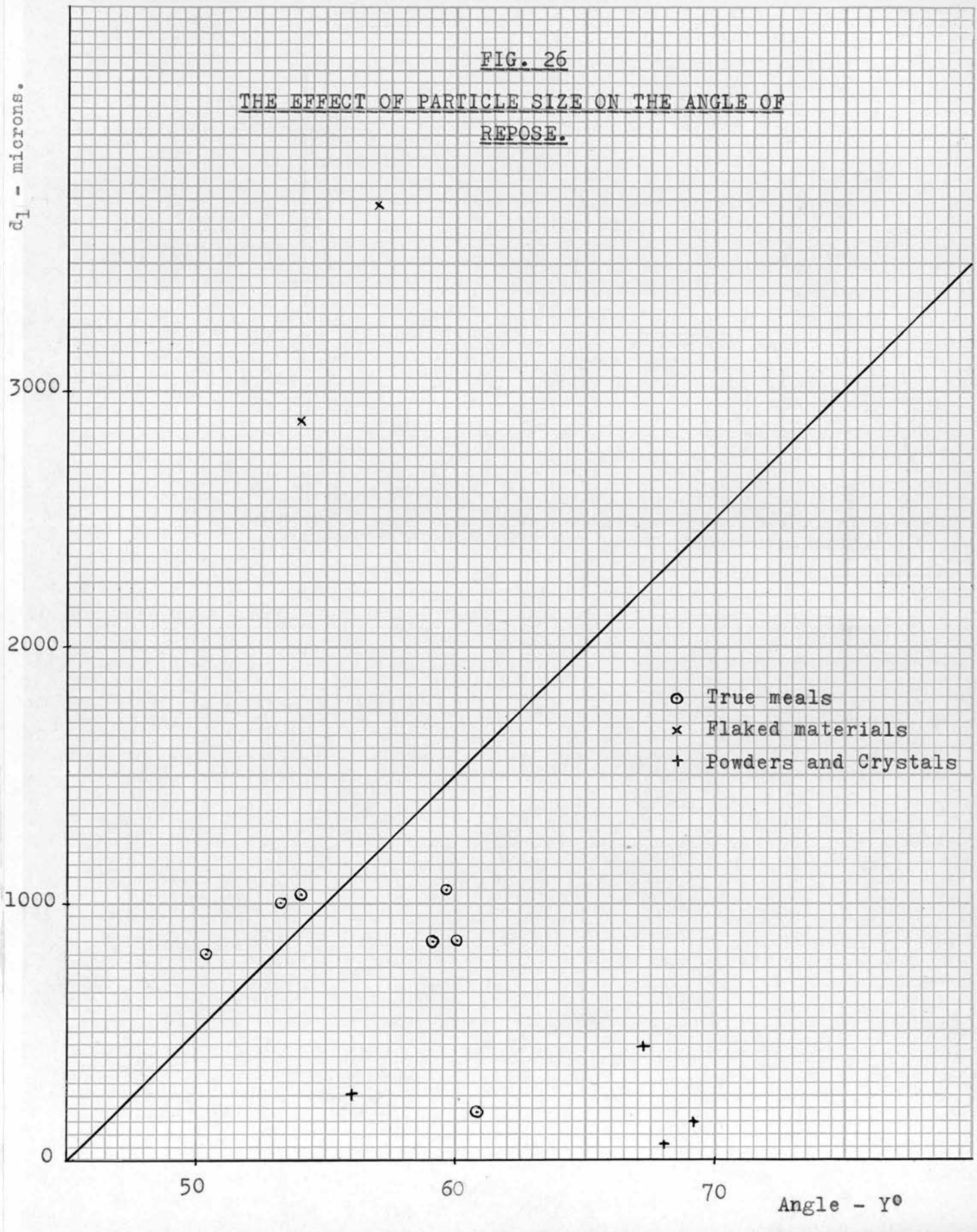


FIG. 26

THE EFFECT OF PARTICLE SIZE ON THE ANGLE OF REPOSE.



particles only, but none were composed of coarse or medium particles only. It was natural that meals with the largest particle size, d_1, also had the largest F.M., the mean diameter of the cereal meals ranged between 250 and 3740 microns but the rest of the meals were all under 1000 microns.

The relationship between d_1 and specific surface, S, was plotted on the graph in Appendix A.13 giving the following equation:-

$$S = 1500 d_1^{0.81}$$

and it followed that $d_p = 1.67 d_1$. The rest of the classified results will be found in Appendix A.14.

5.3 The effect of grinding on particle size.

This effect was examined by graphically plotting values of F.M. against grinder screen hole diameter, d, for ground wheat, oats, barley, milo and beans and the imperical curves in Fig.24 suggested a power relationship. The results of the rectification in Appendix A.15. produced the following relationships.

Wheat	F.M.	$= 5.4 (d)^{0.2}$	+	3.5
Oats	F.M.	$= 5.8 (d)^{0.2}$	+	3.6
Barley	F.M.	$= 6.0 (d)^{0.2}$	+	3.8
Milo	F.M.	$= 5.6 (d)^{0.15}$	+	3.8
Beans	F.M.	$= 3.1(d)^{0.45}$	+	1.6

There was marked similarity about the equations for the cereal meals and they differed from the bean meal, thus indicating a different size reduction process during grinding.

The effect of the size of grinding on the specific surface of barley was shown in Fig. 25, the curve being parabolic.

5.4 The Angle of Repose of Meals.

TABLE 14.

Angle of Repose of Individual Meals.

Meal	Angle°
3/16"ground wheat	57½
¼" ground wheat	50½
3/16" ground barley	59
¼" ground barley	54
crushed oats	54
3/16" ground oats	60
¼" ground oats	53½
Flaked maize	57
¼" ground maize	59½
Soya bean meal	55
Dried grass meal	61
Skimmed milk powder	55
Ground limestone	68
Steamed bone flour	69
Butter salt	67½
Beat No. 10	56

TABLE 15.

Angle of Repose of pairs of meals in equal proportions.

50-50 Meal mixtures	Angle°	Significance
¾" ground barley and dried grass meal	56	**
¼" " " " milk powder	56½	*
¼" " " " butter salt	59	**
¼" " " " ¼" ground oats	54½	**
3/16" ground oats and ¼" " "	56½	**
" " " " dried grass meal	63	**
Butter salt and dried grass meal	61½	**
" " " milk powder	63	**

Table 14 showed that the angle of repose for the meals examined ranged from 50° to 70° and the angle of repose for a mixture of two meals was shown in Table 15 to be the same as the mean angle of the two components. This could be summarised as follows:-

$$Y_{mix} = \frac{\Sigma Y}{N}$$

Where Y was the angle of repose and N the number of components.

The detailed results of this experiment were recorded in the Appendix A.16 and the effect of particle size on Y was shown in Fig. 26.

5.5. The viscosity of meals.

This experiment was carried out with both viscometers and with full-scale and half-scale meals the analysed results being tabulated in Tables 16 and 17, whilst the full test results are recorded in Appendix A.17.

TABLE 16.

Results of Meal Viscosity Experiments

Capacity of Viscometer = 415 ml.

Meal	m.c. %	wt gm.	pa gm/ml	t sec	$\frac{u}{k}$ cm^2/sec
Flaked Wheat	13.9	144	0.35	7.0*	11.61
Broad wheat bran	14.0	90	0.33	5.9	9.64
Fine wheat bran	13.8	182	0.44	2.4	3.39
¼" ground wheat	14.8	253	0.61	2.1	2.85
3/16" ground wheat	14.7	250	0.60	2.0	2.67
⅛" ground wheat	14.7	252	0.61	1.8*	2.30
Crushed oats	13.9	121	0.29	11.8	20.29
¼" ground oats	14.8	154	0.37	6.6	10.91
3/16" ground oats	14.6	148	0.36	5.4	8.65
⅛" ground oats	14.5	153	0.37	5.2	8.40
Flaked maize	14.7	112	0.27	6.9	11.45
Ground maize	14.3	231	0.56	1.1	1.06
¼" ground barley	14.3	244	0.59	4.5	7.15
3/16" ground barley	14.2	244	0.59	3.7	5.71
⅛" ground barley	14.2	242	0.58	3.0	4.46
¼" ground beans	14.6	274	0.66	2.6	3.74
3/16" ground beans	14.6	262	0.63	2.4	3.38
⅛" ground beans	14.6	266	0.64	2.0	2.67
Soya bean meal	9.9	248	0.60	3.2	4.82
¼" ground milo	14.7	275	0.66	1.8	2.31
3/16" ground milo	14.2	279	0.66	1.7	2.13
⅛" ground milo	14.6	276	0.67	1.6	1.95
Groundnut meal	9.8	223	0.54	1.7*	2.13
Dried grass meal	10.2	104	0.25	5.4	8.66
White fish meal	10.8	261	0.63	1.1	1.06
Meat and bone meal	9.8	254	0.61	1.6	1.95
Steam bone flour	10.6	276	0.66	0.9	0.70
Ground limestone	5.6	390	0.94	1.1	1.06
Dairy minerals	4.9	254	0.61	1.3	1.42
Milk Powder	9.5	137	0.33	1.6	1.95
Whey powder	16.1	307	0.74	4.0	6.25
Beta No. 8	11.4	264	0.64	1.0	0.88
Beta No.10	10.7	320	0.77	1.1	1.06
Beta No. 16	11.0	269	0.65	1.7	2.13
Molassine meal	19.4	163	0.39	32.0	56.34
Butter salt	6.6	472	1.14	2.3	3.21

* Converted from large pipe values.

TABLE 17.

Physical properties of half-scale meals

Meal	F.M.	d_l microns	ρ_a gm/ml	t sec	k_u cm^2/sec
Flaked wheat	3.72	1355	0.45	3.6	5.53
Broad wheat bran	2.64	655	0.27	3.5	5.35
Fine wheat bran	0.36	160	0.42	1.2	1.24
¼ ground wheat	2.01	423	0.61	2.3	3.21
3/16" gd.wheat	1.77	357	0.60	2.4	3.38
⅛" ground wheat	1.19	251	0.61	2.6	3.54
Crushed oats	3.80	1366	0.24	7.9	13.24
¼" ground oats	2.28	504	0.35	5.3	8.57
3/16" gd. oats	2.03	428	0.37	5.0	7.03
⅛" ground oats	1.39	275	0.37	3.8	5.89
Flaked maize	4.16	1399	0.30	5.8	9.47
Ground maize	0.94	202	0.45	1.1	1.06
¼" ground barley	2.35	536	0.53	3.8	5.89
3/16" gd.barley	2.06	438	0.53	3.6	5.53
⅛" ground barley	1.41	279	0.52	2.4	3.38
¼" ground barley	2.28	509	0.63	1.7	2.13
3/16" gd.beans	1.73	348	0.59	1.8	2.31
⅛" ground beans	1.19	251	0.59	1.8	2.31
Soya bean meal	1.60	318	0.61	1.4	1.60
¼" ground milo	1.65	328	0.61	1.3	1.41
3/16" gd. milo	1.38	273	0.60	1.4	1.60
⅛" ground milo	1.10	224	0.60	1.3	1.41
Groundnut meal	0.82	233	0.46	1.8	2.31
Dried grass meal	0.22	48	0.24	5.5	8.93
White fishmeal	0.60	160	0.61	1.0	0.38
Meat and Bone meal	1.76	356	0.54	1.7	2.13
Steambone flour	0.19	39	0.58	0.8	0.52
Ground limestone	0.01	2	0.88	2.4	3.38
Dairy minerals	0.06	16	0.60	1.3	1.41
Skimmed milk powder	0.56	154	0.39	1.2	1.24
Whey powder	0.38	136	0.63	3.9	6.06
Beta No. 8	0.66	166	0.61	1.3	1.42
Beta No.10	0.64	163	0.71	1.4	1.69
Beta No.16	0.64	162	0.55	1.2	1.24
Molasses meal	0.82	742	0.42	29.4	58.89
Butter salt	0.36	134	0.97	2.2	3.05

FIG. 27

THE EFFECT OF PARTICLE SIZE ON KINEMATIC VISCOSITY

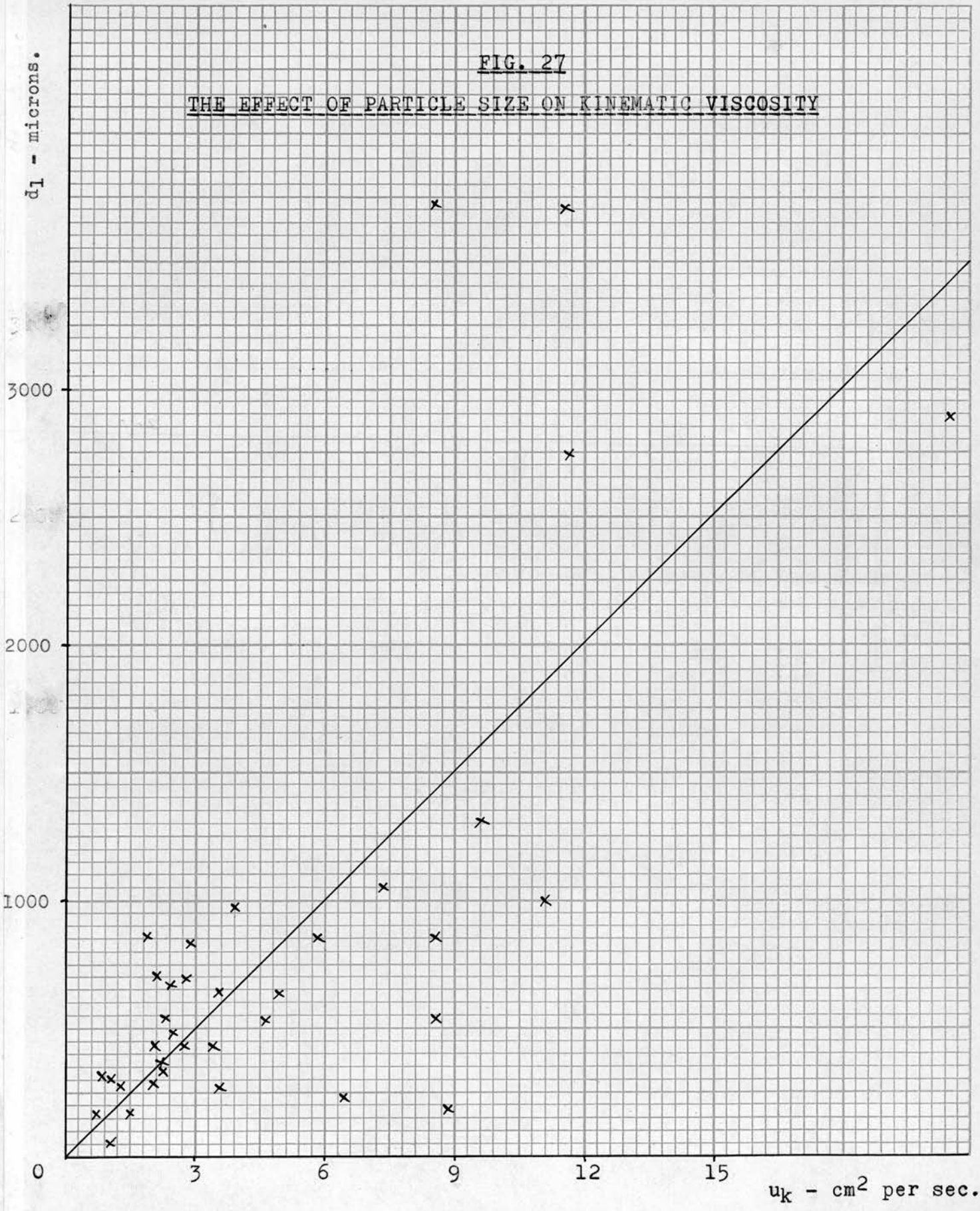
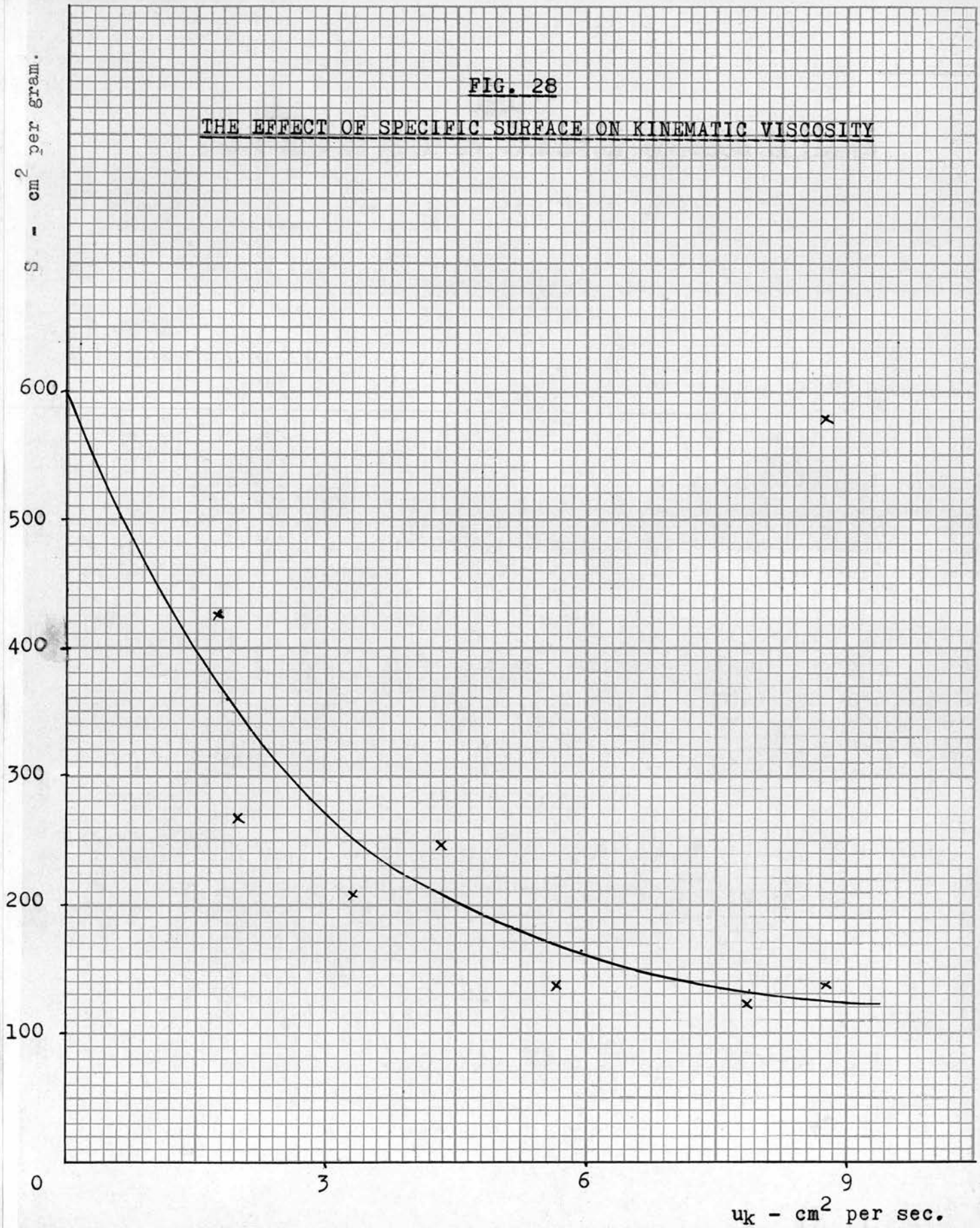


FIG. 28

THE EFFECT OF SPECIFIC SURFACE ON KINEMATIC VISCOSITY



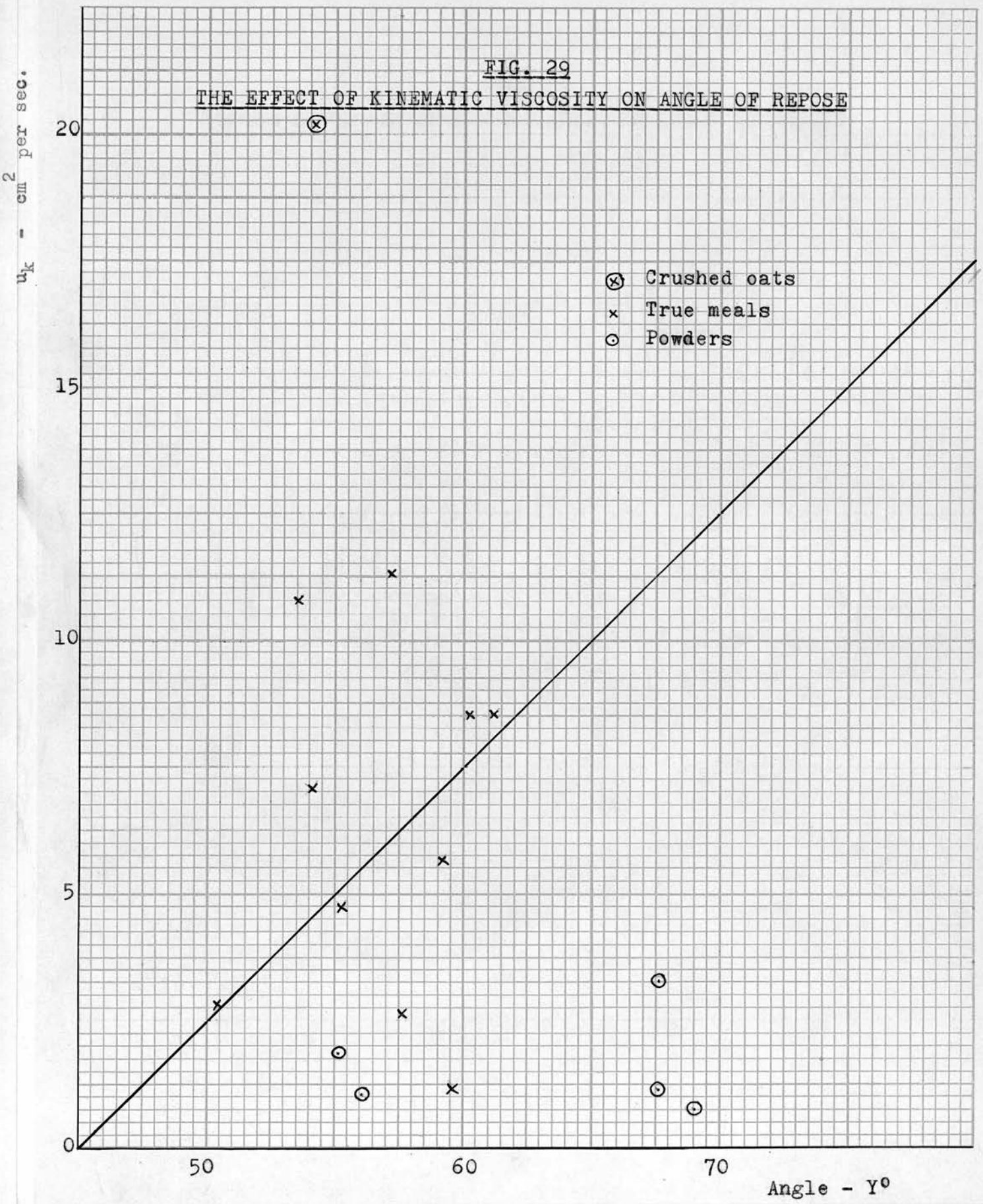
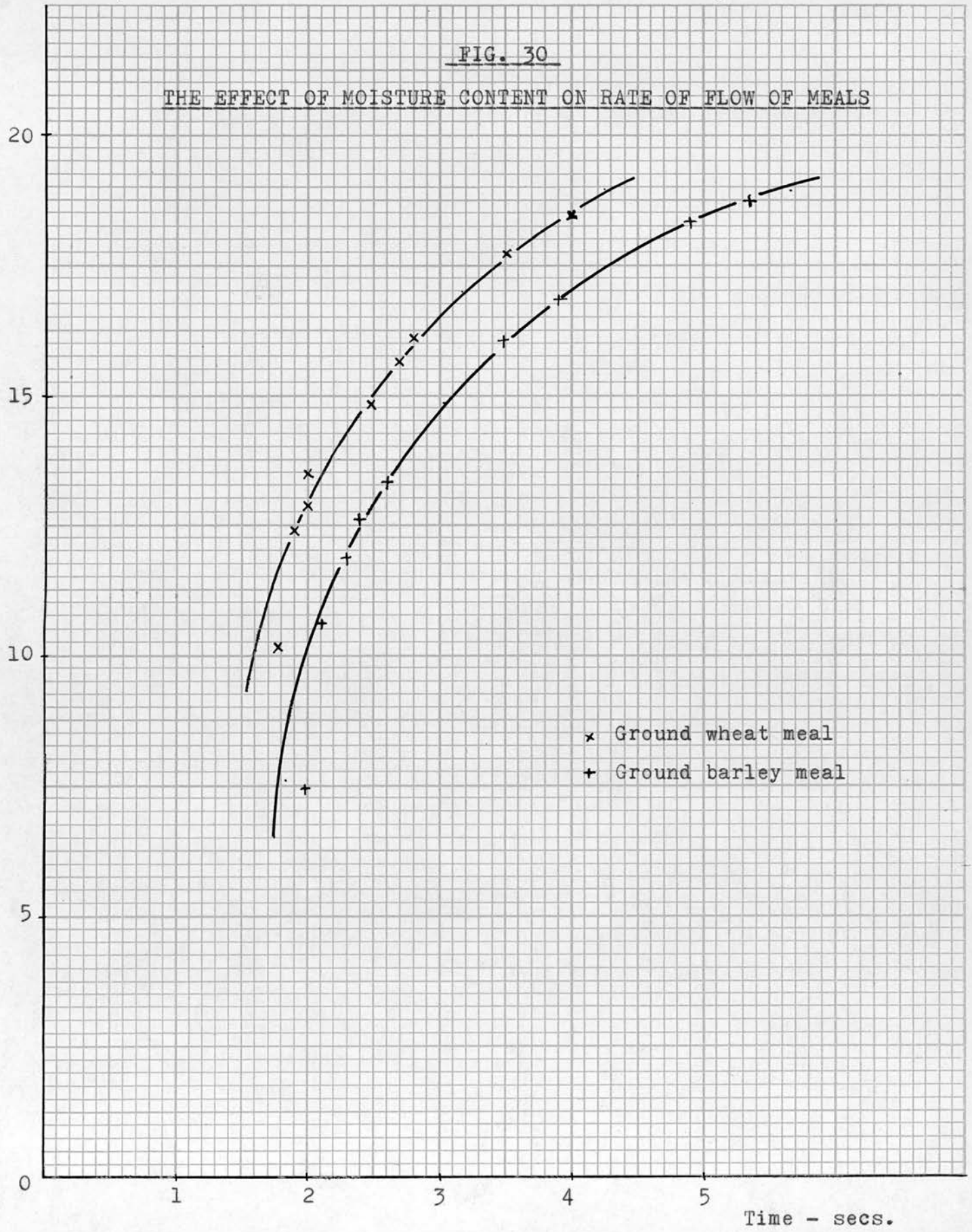


FIG. 29
THE EFFECT OF KINEMATIC VISCOSITY ON ANGLE OF REPOSE
u_k - cm^2 per sec.
20
15
10
5
0
50
60
70
Angle - Y°
Crushed oats
True meals
Powders

FIG. 30

THE EFFECT OF MOISTURE CONTENT ON RATE OF FLOW OF MEALS



The values for kinematic viscosity, u_k, were calculated from the calibration equations determined in section 4.9 for the two viscometers as follows.

Small Viscometer

$$u_k = 1.79t - 0.91$$

Large Viscometer

$$u_k = 0.45t + 0.23$$

To eliminate moisture content variations the meals were dried to approximately the same percentage - namely 14% for the cereals and pulses and 10% for minerals and powders. Temperature had no measurable effect on the viscosity of meals, but the amount of voids had because the most 'open' meals with the smallest apparent density proved to be the most viscous. The effect of particle size on viscosity was shown graphically in Fig.27 and likewise the effect of specific surface in Fig. 28, both substantiated the previous observation that viscosity of a meal was dependant upon the size of its particles and their specific surface.

The following equation relating specific surface, S, to kinematic viscosity, u_k, was rectified in Appendix A.18.

$$S = 600\, u_k^{\frac{2}{3}}$$

In Fig.29 the scatter of plotted points was too great to draw the conclusion that viscosity was related to the angle of repose unless the relationship was masked by other factors such as particle size, specific surface and apparent density.

5.6 The effect of moisture content on viscosity.

Wheat and barley meals of different moisture contents were tested in the small pipe viscometer to observe the effect of moisture content on their viscosity. The weight of each sample tested was noted in case the apparent density varied with moisture content, but this was not so. The classified results are shown in Tables 18A and 18B whilst the complete set of test figures are recorded in Appendix A.19

TABLE 18A

Moisture content results for Barley Meal

M.c	pa	t	uk
%	gm/ml	sec	cm^2/sec
19.1	0.54	5.4	8.86
18.5	0.55	4.9	7.87
17.0	0.56	3.9	6.07
16.3	0.55	3.5	5.35
13.5	0.54	2.6	3.75
12.8	0.55	2.4	3.39
12.1	0.55	2.3	3.21
10.7	0.55	2.1	2.85
7.5	0.54	2.0	2.67

TABLE 18B

Moisture content results for Wheat Meal

M.c	pa	t	u_k
%	gm/ml	sec	cm^2/sec
18.7	255	4.0	6.24
17.9	261	3.5	5.35
16.2	255	2.8	4.10
15.8	258	2.7	3.92
15.0	252	2.5	3.55
13.7	260	2.0	2.67
13.0	255	2.0	2.67
12.5	253	1.9	2.49
10.3	255	1.8	2.31

The rate of flow for each meal was retarded by increasing moisture content as shown by Fig. 30, the curves from which produced the following relationships.

Barley meal

$$t = 1.5M^2 - 28.5M + 15$$

Wheat meal.

$$t = M^2 - 18.5M$$

where t was the rate of flow in seconds and M the % moisture content. Full details for developing these results are given in Appendix A19.

5.7 The effect of the porosity and bulkiness of meals.

Porosity of the meals examined was expressed as a percentage of voids and bulkiness as the inverse of apparent density and tabulated in Table 19, which was compiled from data in previous experiments.

The results, tabulated in ascending order of bulkiness, did not show any definite relationships between bulkiness, length mean diameter, porosity and specific surface, but a trend existed showing a tendancy for larger particles, greater porosity and greater specific surface to increase the bulkiness of a meal. It was impossible to produce a curve by plotting bulkiness, B, against d_l, but the approximate curves for B versus P and B versus S in Fig.31 gave the approximate relationships:-

$$B = \frac{3S}{400} = \frac{3}{80-P}$$

These relationships were complicated by the heterogenous properties of individual meal particles which made their behaviour difficult to predict; further investigation was thought to be beyond the scope of this study at present and it was passed over in favour of the investigation of more practical aspects of mixing.

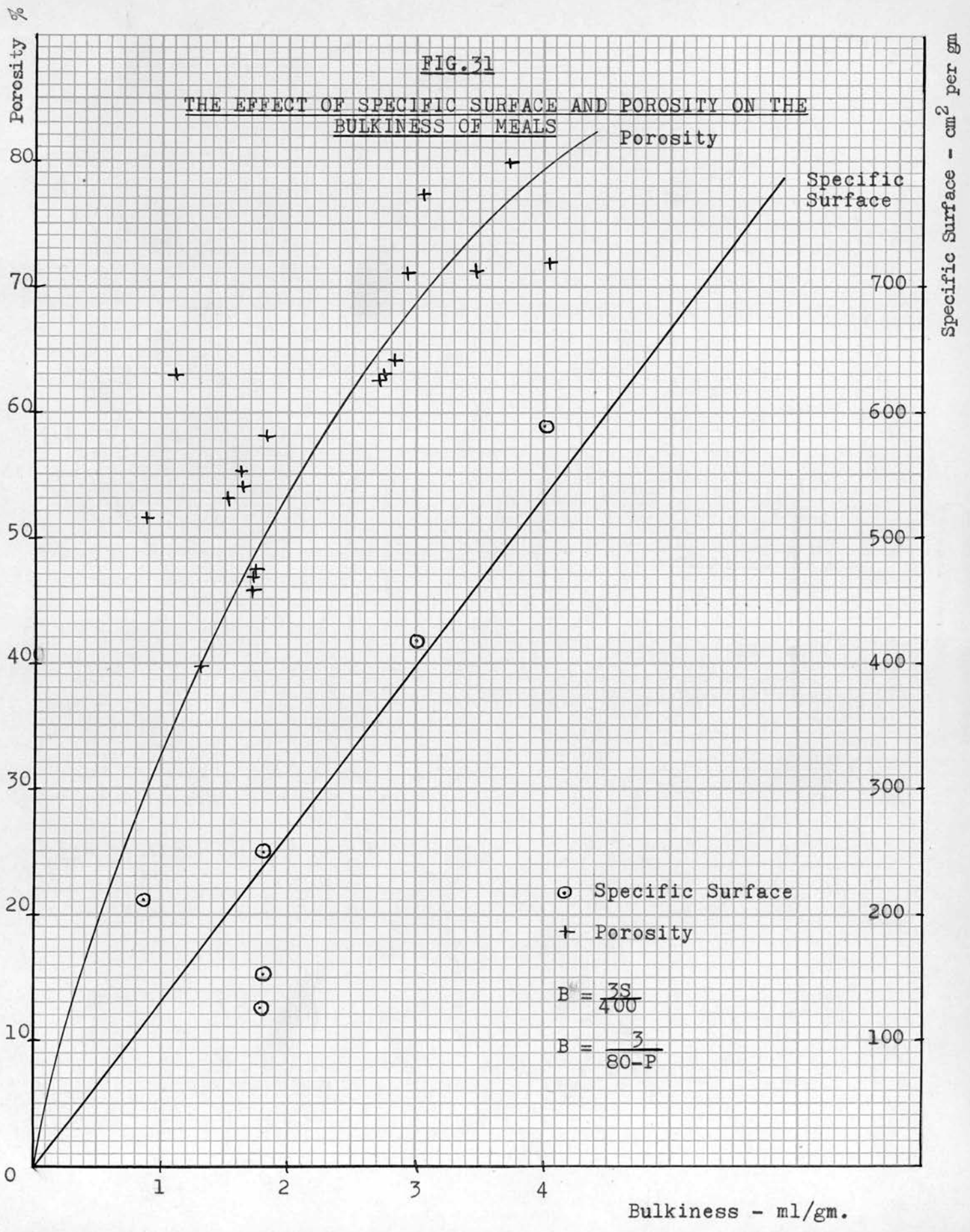


FIG.31
THE EFFECT OF SPECIFIC SURFACE AND POROSITY ON THE BULKINESS OF MEALS
Porosity %
Specific Surface - cm² per gm
Porosity
Specific Surface
80
70
60
50
40
30
20
10
0
700
600
500
400
300
200
100
1
2
3
4
Bulkiness - ml/gm.
⊙ Specific Surface
+ Porosity
B = 3S/400
B = 3/(80-P)

TABLE 19.

The porosity and bulkiness of meals

Meals.	Bulkiness	d_1	Porosity	S
	ml/gm	Microns	%	cm^2/gm
Butter salt	0.88	408	51.5	211
Ground limestone	1.06	32	62.8	-
Beta No.10	1.30	271	38.9	-
Steambone flour	1.52	151	32.8	-
¼" ground beans	1.52	971	52.9	-
⅛" ground beans	1.56	420	54.3	-
3/16" ground beans	1.59	638	55.0	-
White fish meal	1.59	263	54.6	-
¼" ground wheat	1.64	811	50.0	-
⅛" ground wheat	1.64	466	50.0	-
3/16" ground wheat	1.66	675	50.8	-
¼" ground barley	1.70	1044	46.3	125
3/16" ground barley	1.70	841	46.3	153
⅛" ground barley	1.72	518	47.3	250
Ground maize	1.79	374	58.2	-
¼" ground oats	2.70	1003	63.0	-
⅛" ground oats	2.70	529	63.0	-
3/16" ground oats	2.78	857	64.0	-
Flaked wheat	2.86	2770	71.3	-
Skimmed milk powder	3.03	173	77.4	415
Crushed oats	3.44	2905	71.0	-
Flaked maize	3.71	3740	79.9	-
Dried grass meal	4.00	188	71.9	587

INVESTIGATION OF MIXER DESIGN FACTORS.

5.8 Testing the model mixer.

The factors affecting the scaling down of a meal mixer were tested with two different mixes in the full-size Reffold mixer and the experimental model mixer. The two mixes differed widely being (1) 50% barley meal plus 50% dried grass meal and (2) 99% barley meal plus 1% butter salt. The values of the Uniformity Index for each mixing time were recorded in Tables 20 and 21 and the individual results classified in Appendix A.20

TABLE 20

50-50 Dried grass + barley meal Uniformity Indices

Model		Prototype	
Time Min.	Uniformity Index.	Time Min.	Uniformity Index.
2.0	.772	2.8	.354
4.0	.702	5.7	.339
6.0	.577	8.5	.293
8.0	.445	11.5	.261
10.0	.549	14.1	.205
12.0	.496	17.0	.254
14.0	.486	19.8	.225
16.0	.374	22.6	.219
20.0	.365	28.3	.158
25.0	.257	35.3	.121
30.0	.242	-	-
35.0	.167	-	-

TABLE 21

1-99 Salt + Barley meal - Uniformity Indices

Model		Prototype	
Time Min.	Uniformity Index	Time Min.	Uniformity Index
2.5	.097	3.5	.067
5.0	.061	7.1	.053
7.5	.051	10.6	.044
10.0	.043	14.1	.028
12.5	.028	-	-
15.0	.022	21.2	.020
20.0	.021	28.3	.021
25.0	.024	-	-
30.0	.026	42.5	.025
35.0	.024	-	-
40.0	.028	-	-
-	-	63.7	.032

The results showed that the mixing in the half-scale mixer was representative of that occurring in the full-size machine provided that standardised procedures were carried out for each mixture. The main

difference was the degree of mixing that occurred at in-feeding. The mix in the model had not reached the same standard of uniformity as the prototype at the start of each experiment, i.e. after all ingredients had bee introduced, but after this the rate of mixing was exactly the same for both mixers. The Uniformity of mixing wae an exponential function of time in both mixers, the forms of the equations being:-

50-50 dried grass meal and ¼" ground barley.

(1) Model: $U.I. = 0.85e^{0.56t}$

(2) Prototype: $U.I. = 0.42e^{0.56t}$

The degree of uniformity being 0.85 and 0.42 respectively at zero time.

1-99 Butter salt and 3/16" ground barley.

(1) Model: $U.I. = 0.12e^{1.48t}$

(2) Prototype: $U.I. = 0.10e^{1.47t}$

The degree of mixing at any time was almost identical in each mixer with these two rapid mixing ingredients.

The uniformity index at any time for the two mixes differed by 0.43 and 0.02 respectively and these differences were the same as those displayed at the start of recording. Graphical results are shown in Figs32 and 33.

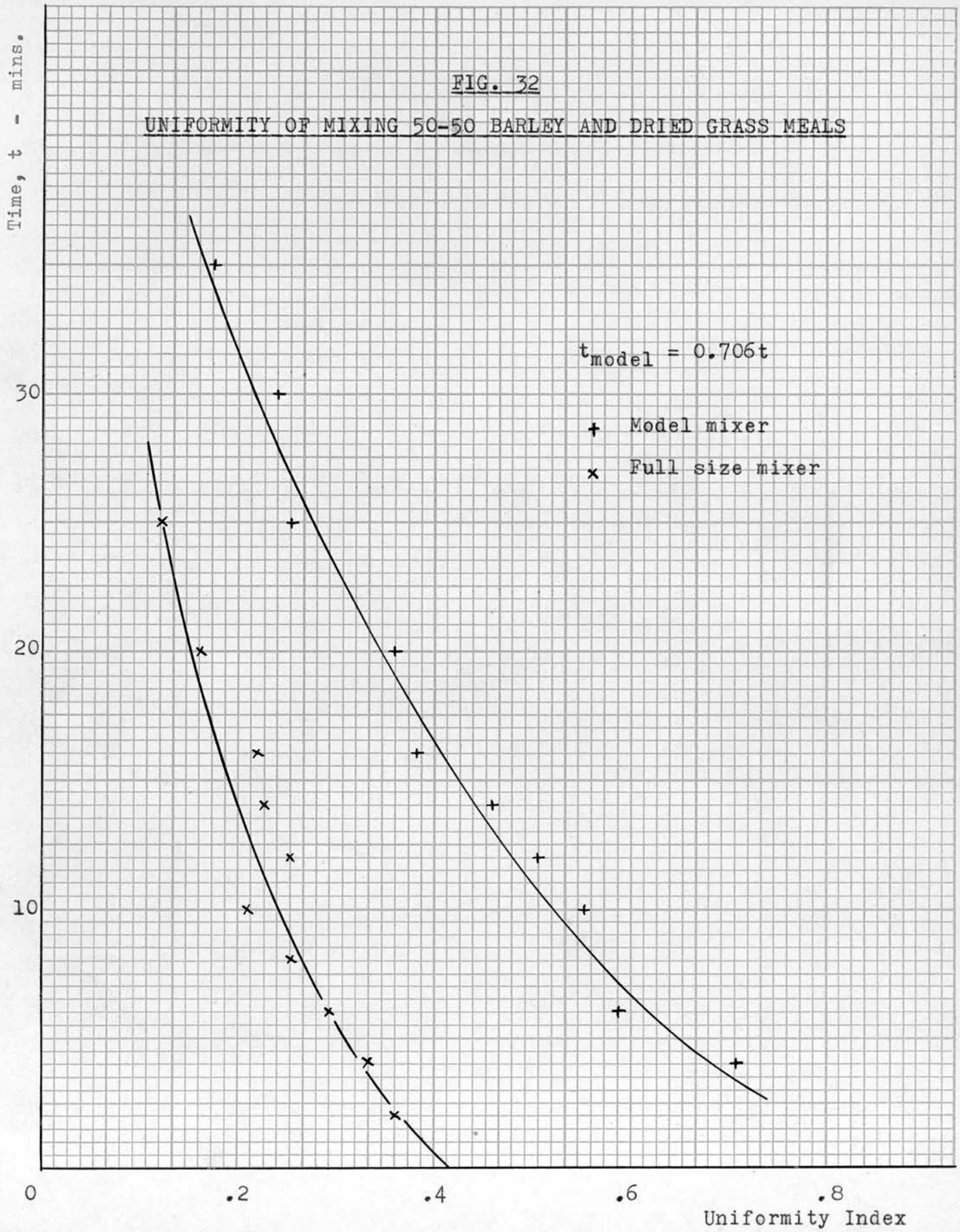
5.9 The effect of time on the uniformity of mixing.

In order to extend the range of meal types studied a third mix was investigated under the same conditions as those described in the previous section. The mix was composed of 20% skimmed milk powder and 80% ground barley meal and the results are tabulated below. The mixing curve was compared with those from later experiments with 20/80 mixes of dried grass and salt with barley meal. It is recorded in Fig.34.

Seperate analyses were performed on the barley meal for starch and fibre and the results showed that the fibre tended to be dispersed more readily than the starch particles. The fibre proportion was less than the starch proportion, the mix being proportioned as follows:-

FIG. 32

UNIFORMITY OF MIXING 50-50 BARLEY AND DRIED GRASS MEALS



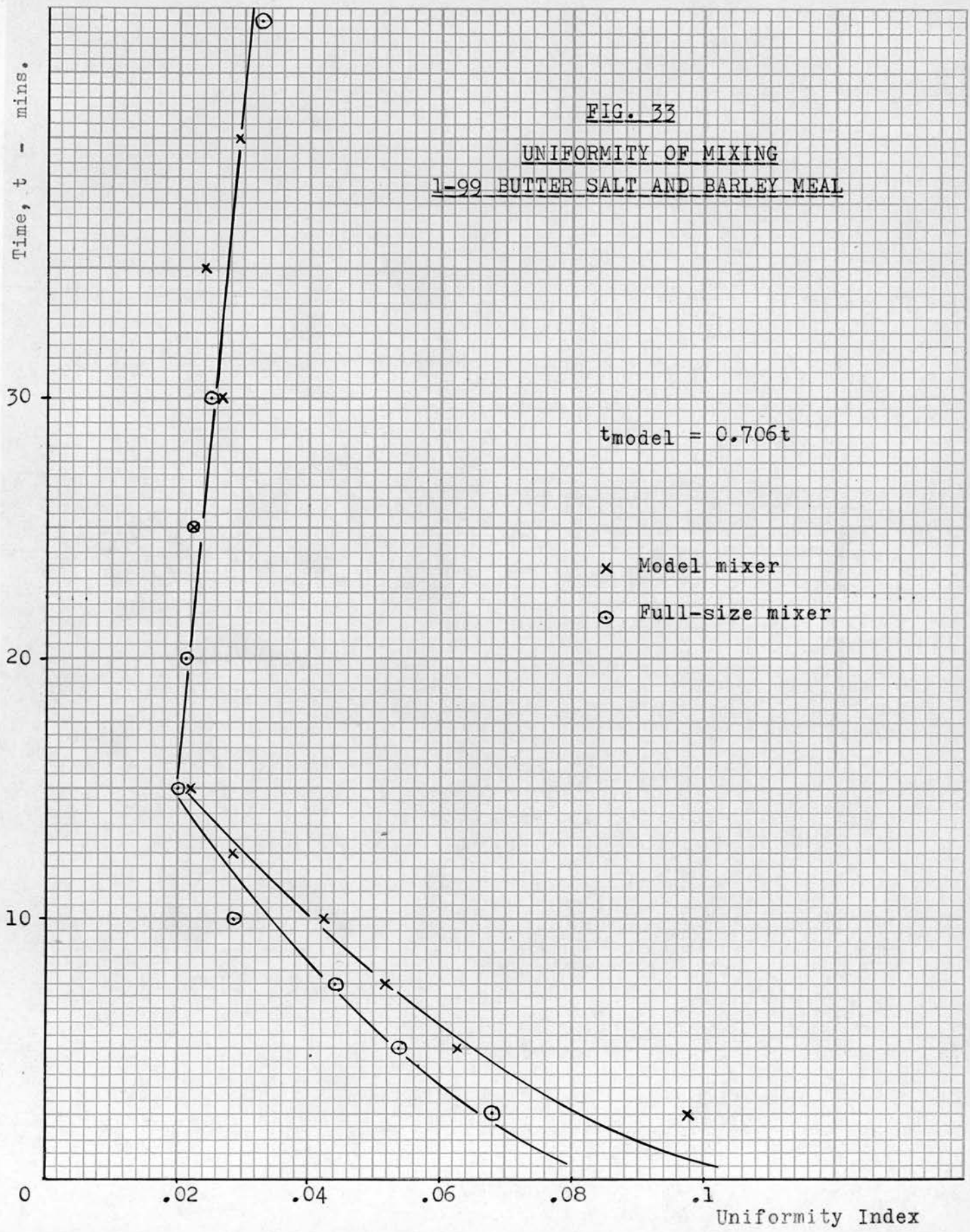
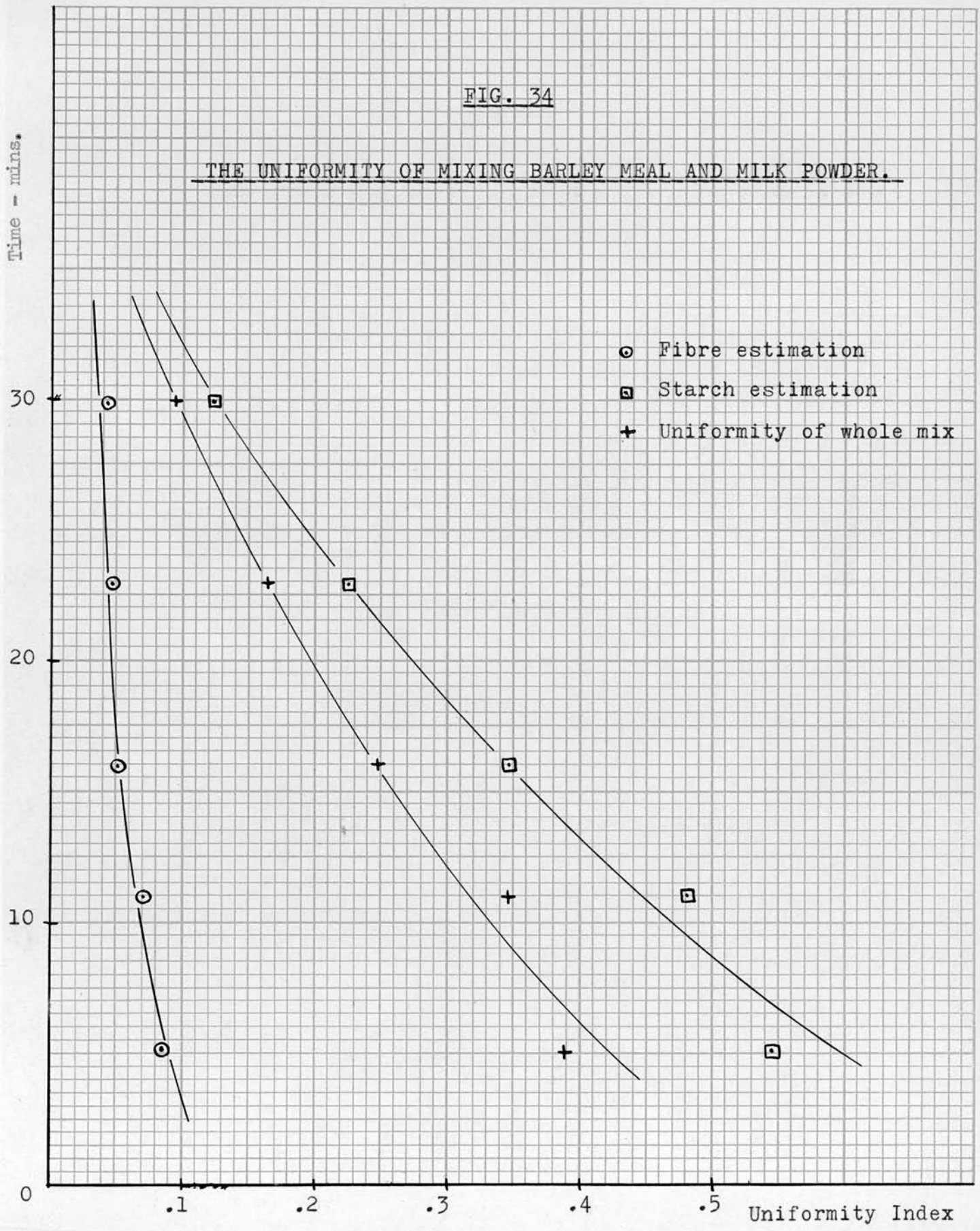


FIG. 33
UNIFORMITY OF MIXING
1-99 BUTTER SALT AND BARLEY MEAL
Time, t - mins.
30
20
10
0
.02
.04
.06
.08
.1
Uniformity Index
$t_{model} = 0.706t$
× Model mixer
⊙ Full-size mixer

FIG. 34

THE UNIFORMITY OF MIXING BARLEY MEAL AND MILK POWDER.



0.20 skimmed milk powder
0.19 barley fibre
0.61 barley starch.

The exponential equation for the mixing of the 20/80 milk powder and barley meal mix, when the uniformity was estimated by starch analysis, was found to be:-

$$U.I = 0.80e^{0.75t}$$

The detailed results were recorded in Appendix A.21.

TABLE 22

Uniformity of mixing barley meal and milk powder.

Time	Uniformity Index	
Min.	Starch	Fibre
5	0.541	0.082
11	0.486	0.068
16	0.348	0.052
23	0.223	0.045
30	0.122	0.041

5.10 The effect of mixer in-feed position.

This experiment compared the top-feed and bottom-feed versions of the model mixer using the 20/80 milk powder and barley meal results from section 5.9 for the bottom-feed mixer and the results in Table 23 for the top-feed mixer. A duplicate experiment was performed with a 10/90 mix of dried grass and barley meals with the results shown in Table 24.

TABLE 23

20/80 Milk Powder and Barley Meal.

Time	Uniformity Index	
Min.	Bottom-feed	Top-feed
10	0.452	0.296
20	0.261	0.165
30	0.127	0.078

TABLE 24.

10/90 Dried Grass and Barley Meals.

Time	Uniformity Index.	
Min.	Bottom-feed	Top-feed.
5	0.248	0.340
15	0.173	0.217
25	0.136	0.165

The graphic results in Fig.35 showed that a higher degree of initial mixing occurred with the top-feed mixer although both curves indicated an exponential equation. The full results are recorded in Appendix A.21 and A.22.

5.11 The effect of auger speed.

Five different speeds were used to investigate the effect of auger speed on the uniformity of mixing. The results for a 20/80 milk powder and barley meal mix were recorded in Table 25 and for a 1/99 salt and barley meal mix in Table 26.

TABLE 25.

20/80 Milk Powder and Barley Meals.

Auger Speed	Uniformity Index	
r.p.m.	After 10 mins.	After 20 mins.
85	0.453	0.249
153	0.223	0.165
189	0.296	0.165
262	0.398	0.275
352	0.630	0.581

TABLE 26.

1/99 Salt and Barley Meal.

Auger Speed r.p.m.	Uniformity Index After 20 minutes.
86	0.052
152	0.019
194	0.020
265	0.091
350	0.138

The first mix showed an optimum auger speed of approximately 175 r.p.m. and the second approximately 155 r.p.m. by plotting the results graphically in Fig. 36. At the slowest speeds 'bridging' occured and the movement of the meals at the periphery of the mixing chamber was retarded because the centrifugal momentum imparted to the particles by the auger was inadequate. The highest speeds gave a widespread centrifugal despersion with the trajectories of the meal particles being easily visible; at the highest speeds separation of particles according to size occured, the finer ones aggregating around the periphery.

The complete results for these two different mixes were tabulated for comparison in Appendix A.23.

5.12 The effect of the mixing chamber size.

The size of the mixing chamber was increased in 0.66 cu. ft. stages by increasing the height for a constant diameter and the uniformity of mixing results are shown in Table 27 below.

TABLE 27.

20/80 Milk Powder and $\frac{1}{4}$" Barley Meal

Size	Mixing Chamber Width/depth	Volume ($ft.^3$)	Uniformity Index
24" x 22"	0.92	5.28	0.360
21" x 22"	1.05	4.62	0.219
18" x 22"	1.22	3.96	0.165
15" x 22"	1.47	3.30	0.126
12" x 22"	1.83	2.64	0.134

These results expressed graphically in Fig. 37 indicated a power relationship between Uniformity Index and ratio of mixing chamber width to

depth. The greatest degree of uniformity under the conditions of this mix would appear to be achieved when the ratio was approximately 1.55.

The full results will be found in Appendix A.24.

5.13 The effect of shrouding the mixing auger.

This examination was carried out with a 20/80 mix of powder and barley meal once more; the test in section 5.10 with the top-feed mixer and shrouded auger was repeated without the auger shroud. The results are shown in Table 28 and Fig.38

TABLE 28

20/80 Milk Powder and $\frac{1}{4}$" Barley Meal

Time Mins	Uniformity Index	
	Shrouded Auger	Un-shrouded Auger
10	0.296	0.386
20	0.165	0.182
30	0.078	0.090

The results showed that there was an advantage to be gained by fitting a cylindrical shroud around the upper mixing auger because of the greater mix uniformity at a given time; the difference in Uniformity Indices was greatest after 10 minutes mixing and it decreased as the mix became more uniform. The individual results are recorded in Appendix A.25.

5.14 The effect of spreading blades on the mixing auger.

The same conditions prevailed for this examination as the previous one in section 5.13 and once again the results from section 5.10 were used as a comparison. The effect of spreading blades on the uniformity of mixing is shown in Table 29 and Fig.39.

TABLE 29

Time Mins	Uniformity Index	
	Blades	No Blades
10	0.264	0.296
20	0.150	0.165
30	0.076	0.078

The Uniformity Indices for the test when spreading blades were fitted proved to be smaller than those without blades, the difference was more noticeable after 10 minutes than 30 minutes. The full results are recorded in Appendix A.26.

Fig. 35

THE EFFECT OF IN-FEED POSITION ON THE UNIFORMITY OF MIXING

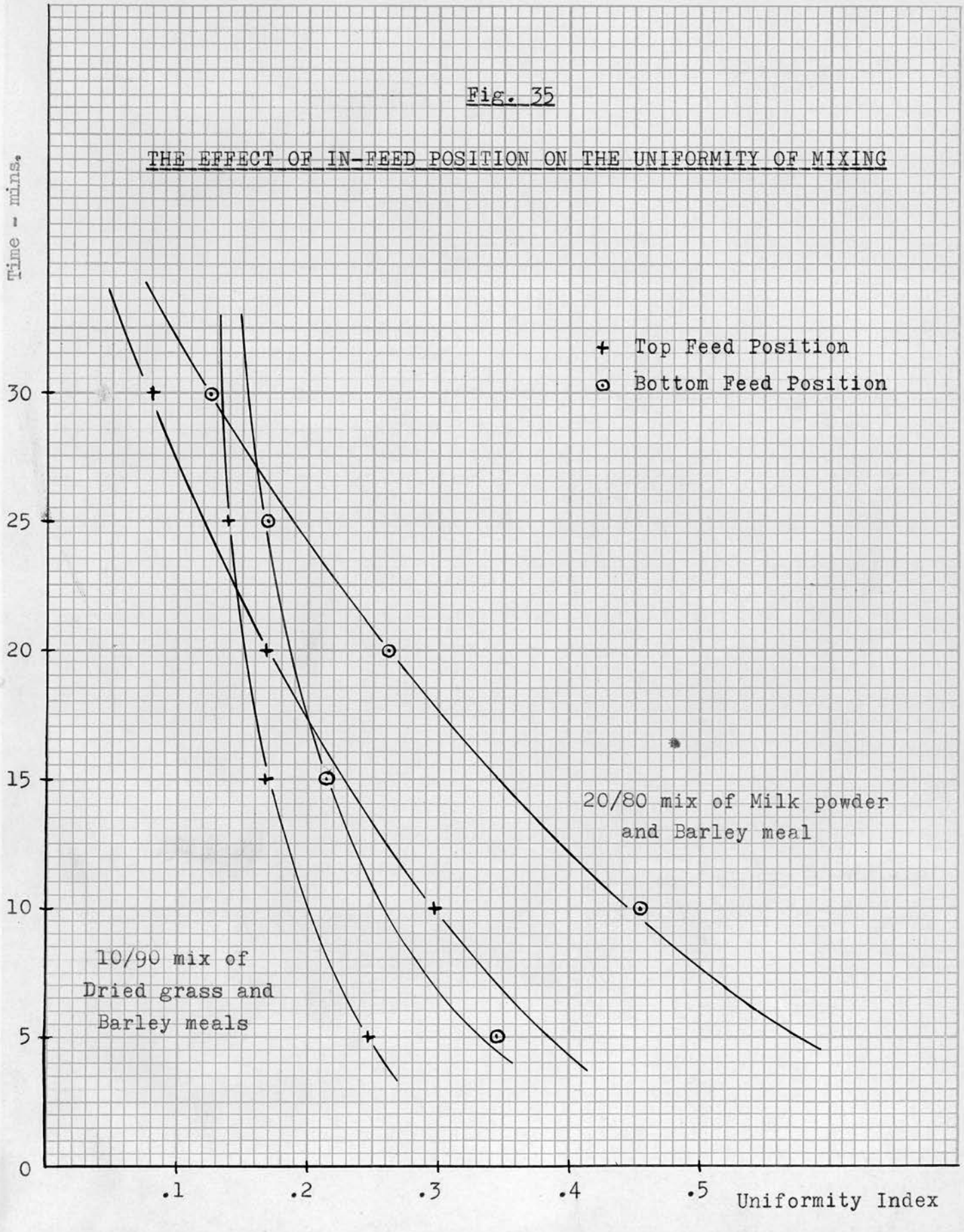


FIG. 36

THE EFFECT OF AUGER SPEED ON UNIFORMITY OF MIXING

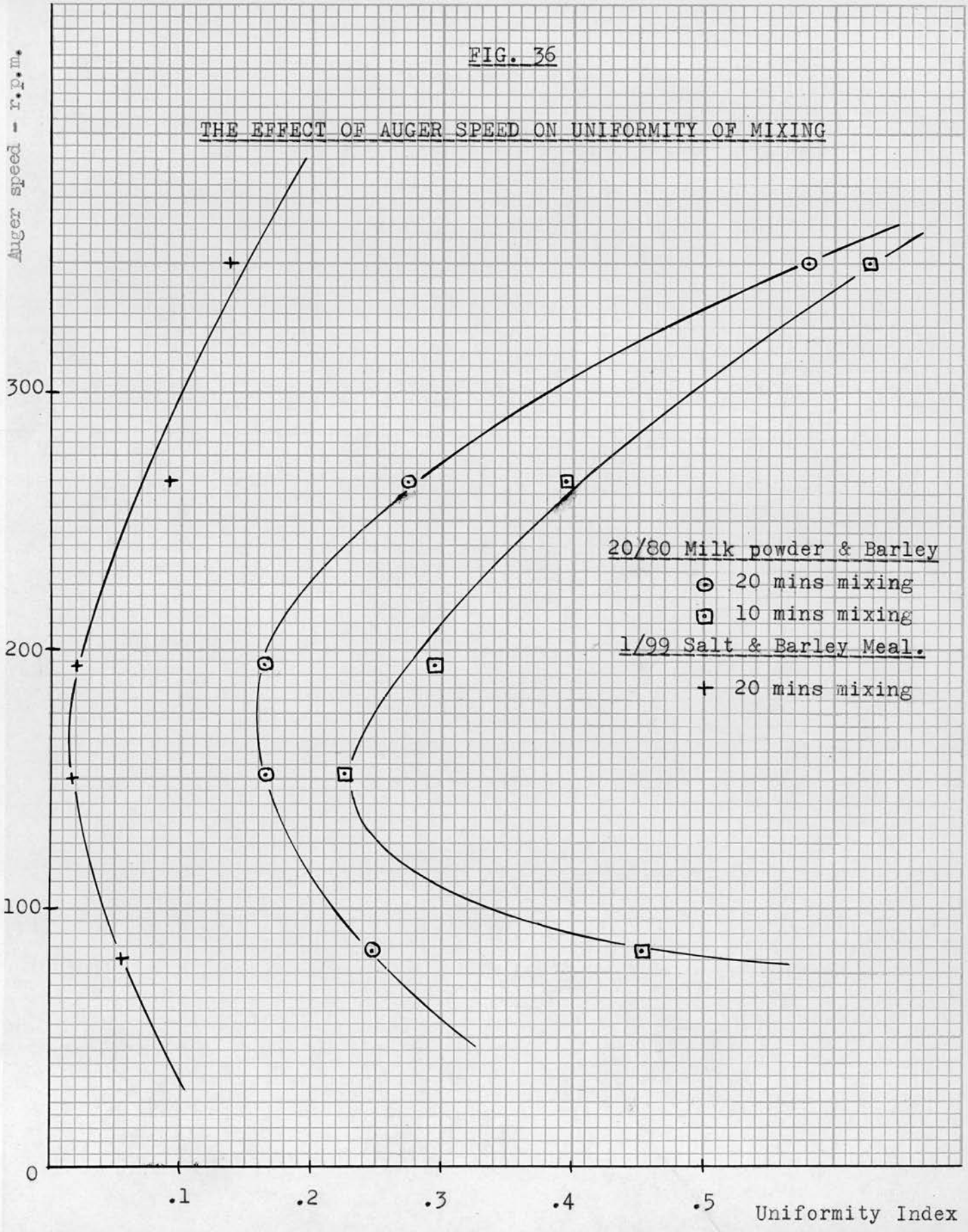


FIG. 37

THE EFFECT OF MIXING CHAMBER PROPORTIONS ON THE UNIFORMITY OF MIXING.

20/80 mix of milk powder and barley meal after 20 minutes mixing.

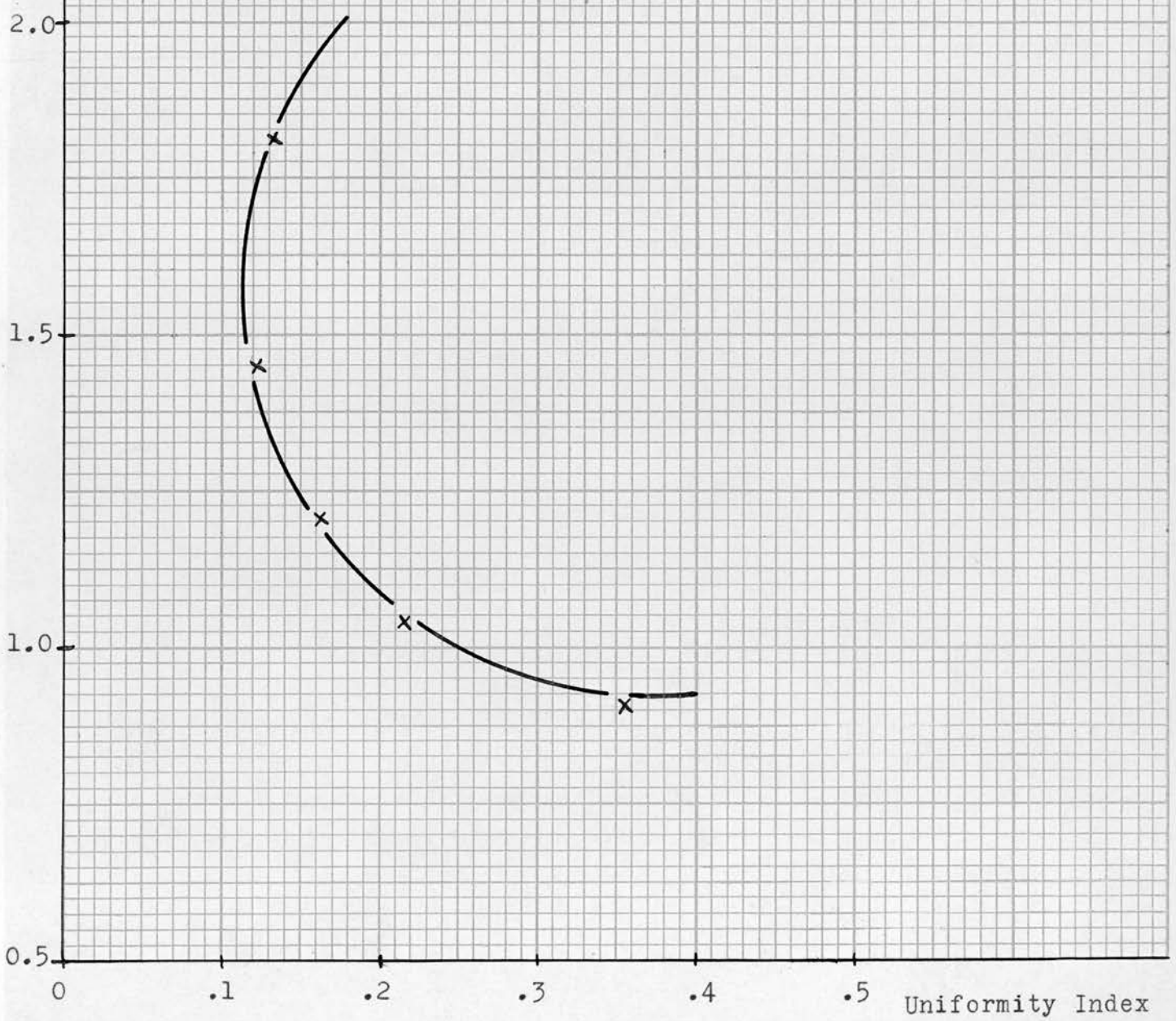


FIG. 38

THE EFFECT OF AUGER SHROUD ON THE UNIFORMITY OF MIXING

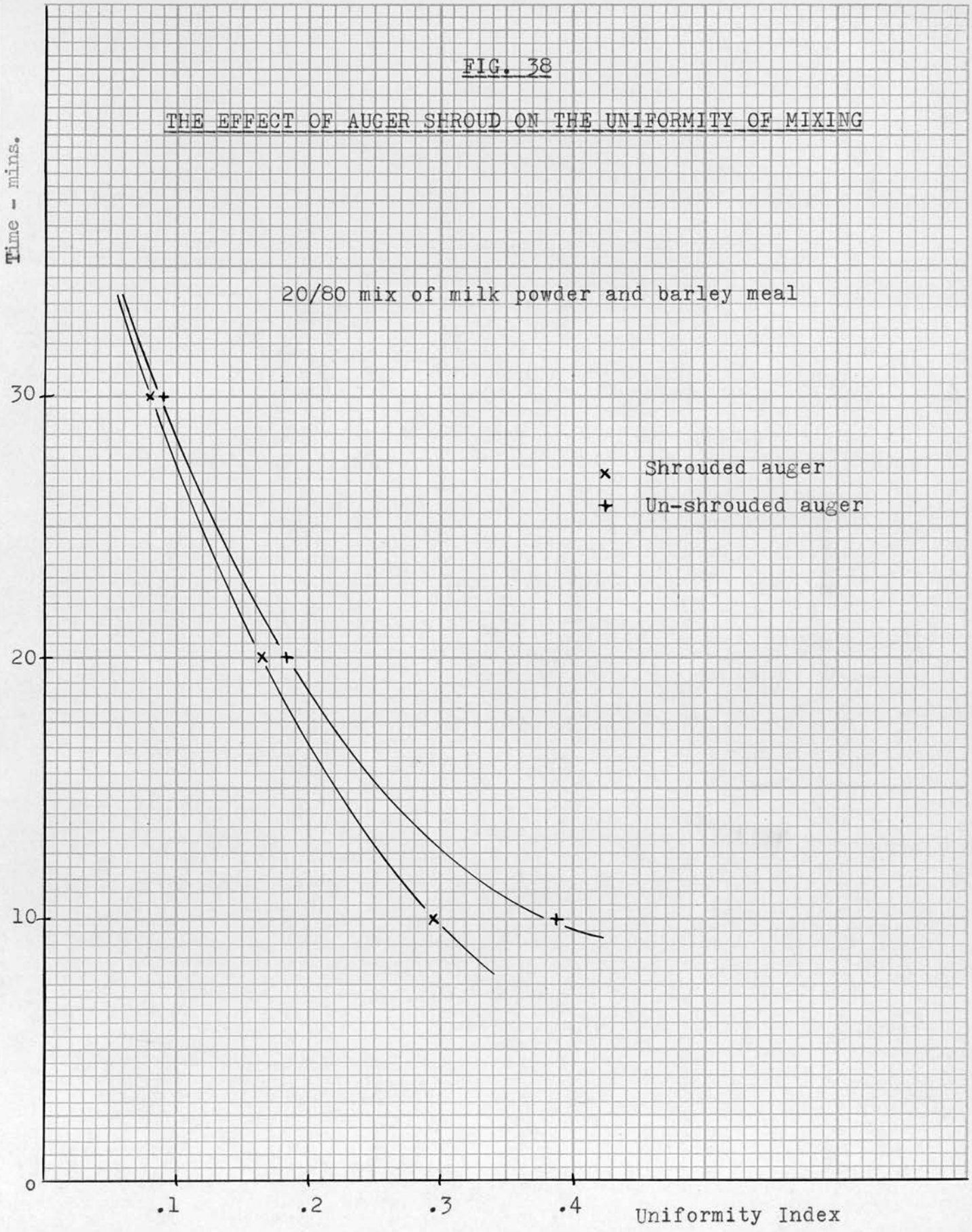
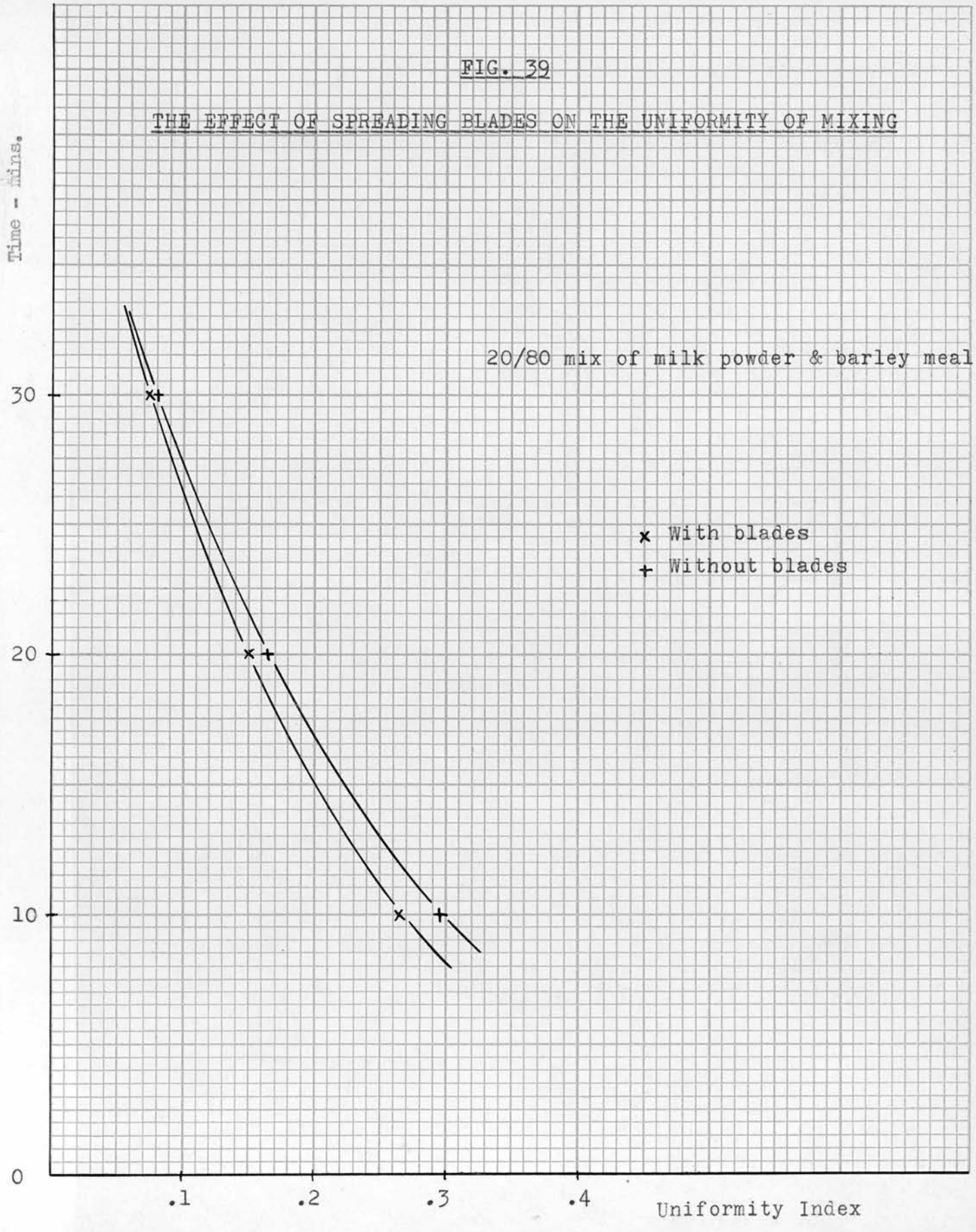


FIG. 39

THE EFFECT OF SPREADING BLADES ON THE UNIFORMITY OF MIXING



5.15 The effect of different proportions of the mix components.

This examination was performed in the model mixer with a series of mixes containing different proportions of dried grass and ground barley peals - the range being 50/50 to 5/95. The results were tabulated in Appendix A.27 and summarised in Table 30 below.

TABLE. 30.

Uniformity of different dried grass proportions.

Time Mins.	Uniformity Index of different dried grass proportions.			
	0.5	0.25	0.1	0.05
5	0.660	-	0.248	0.075
10	0.549	0.351	-	-
15	0.491	-	0.173	0.066
20	0.365	0.274	-	-
25	0.257	-	0.136	0.060
30	0.242	0.162	-	-

The figures showed that the smaller the proportion of dried grass meal the more uniform was the mix at any time, but the curves in Fig.40 indicated that a completely uniform mix (U.I = 0) would be achieved only after a considerable period of mixing. These curves were produced from exponential equations but the relationship between the proportion of driend grass and the uniformity of the mix was parabolic; it is shown in Fig. 41. The equation for mixes of dried grass meal and ¼" ground barley after 20 mins. mixing was

$$U.I. = 0.033x^{0.63}$$

Where x was the proportion of dried grass in the mix (see Appendix A.27).

It could be concluded from this investigation that the component proportions were functions of their mixing ability and that the time to reach uniformity was reduced as the difference between the proportions of two components increased.

5.16 The effect of viscosity on the mixing of meals.

The data on 20/80 mixes of dried grass meal, skimmed milk powder and salt with barley meal was collected and the product of the kinematic viscosities of the components and the Uniformity Index of the mix shown in Table 31. Since barley fibre comprised approximately 20% of the 20/80 mix of milk powder and barley meal its values were included also; the U.I. value for that mix as a whole was the combined value for both barley fibre and barley starch - called U_z in

section 2.24. The standard time of mixing was taken as 20 minutes.

TABLE 31.

The effect of viscosity on the U.I. of 20/80 mixes.

Ref.	Meal Mixes	U.I.	Product of viscosities.
A	Dried grass / ¼" barley	0.198*	61.96
B	Salt / ¼" barley	0.091	22.94
C	Salt / 3/16" barley	0.056	18.30
D	Milk Powder / ¼" barley	0.197*	13.95
E	Fibre / barley, starch & milk	0.045*	13.95
F	Salt / dried grass	0.115	27.80

* indicated values from mixing curves.

Fig. 42 showed the graphical plots for these values and indicated a straight-line relationship between U.I. and the product of the kinematic viscosity of the two components of the mix. The plot for mix D disagreed with this conclusion, so it appeared that the U.I. value had to be determined by the analysis of components with the same proportion, i.e. in this case the U.I. of D should have been obtained by analysis of the milk powder. The value used for D was the mean of the two barley meal fractions that, together, composed 80% of the mix, whilst all other U.I. values were obtained from the 20% component.

To increase the reliability of the curve a further test was carried out for a 20/80 mix of salt and dried grass meal and recorded in Appendix A.28, it followed the same pattern as the others and the equation for the relationship was assumed to be:-

$$U.I. = 1/3\, u_k' u_k''$$

Where u_k' and u_k'' were the kinematic viscosities of the two components.

5.17 The effect of particle size characters on mixing.

It was impossible to obtain a definite relationship between particle size or shape and the uniformity of mixing because of the number of factors involved and the limited amount of data that could be obtained for each mix at one time. From the equations derived in sections 5.5 and 5.16 it would appear that specific surface as a measure of particle size and shape could be related to the uniformity of mixing by the following equation.

$$U.I. = \frac{1}{\text{const}} (S'.S'')^{0.67}$$

FIG. 40

THE EFFECT OF DIFFERENT DRIED GRASS PROPORTIONS ON UNIFORMITY

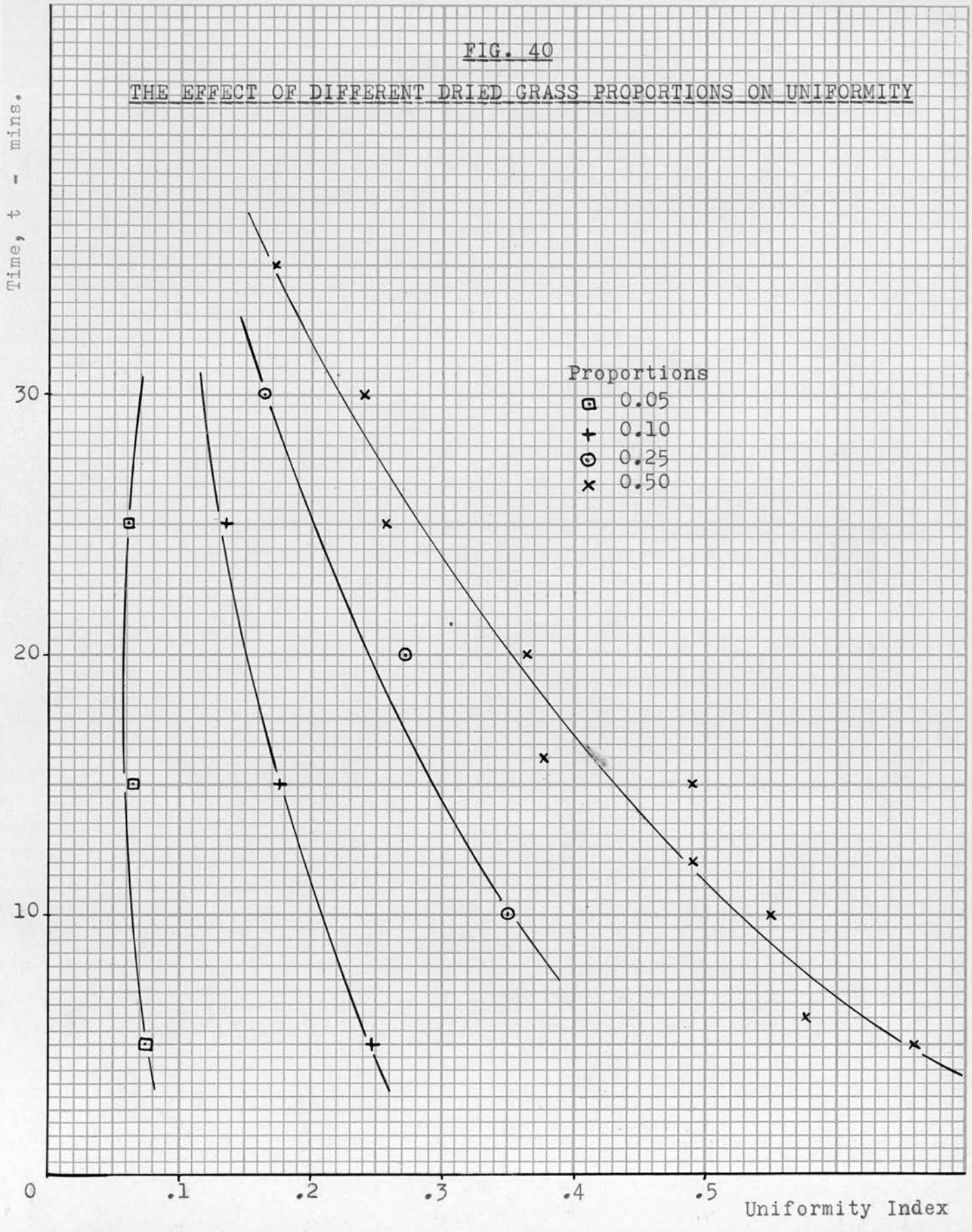


FIG. 41

THE EFFECT OF INGREDIENT PROPORTION ON UNIFORMITY

Mix of ground barley and dried grass meals
at time = 20 mins.

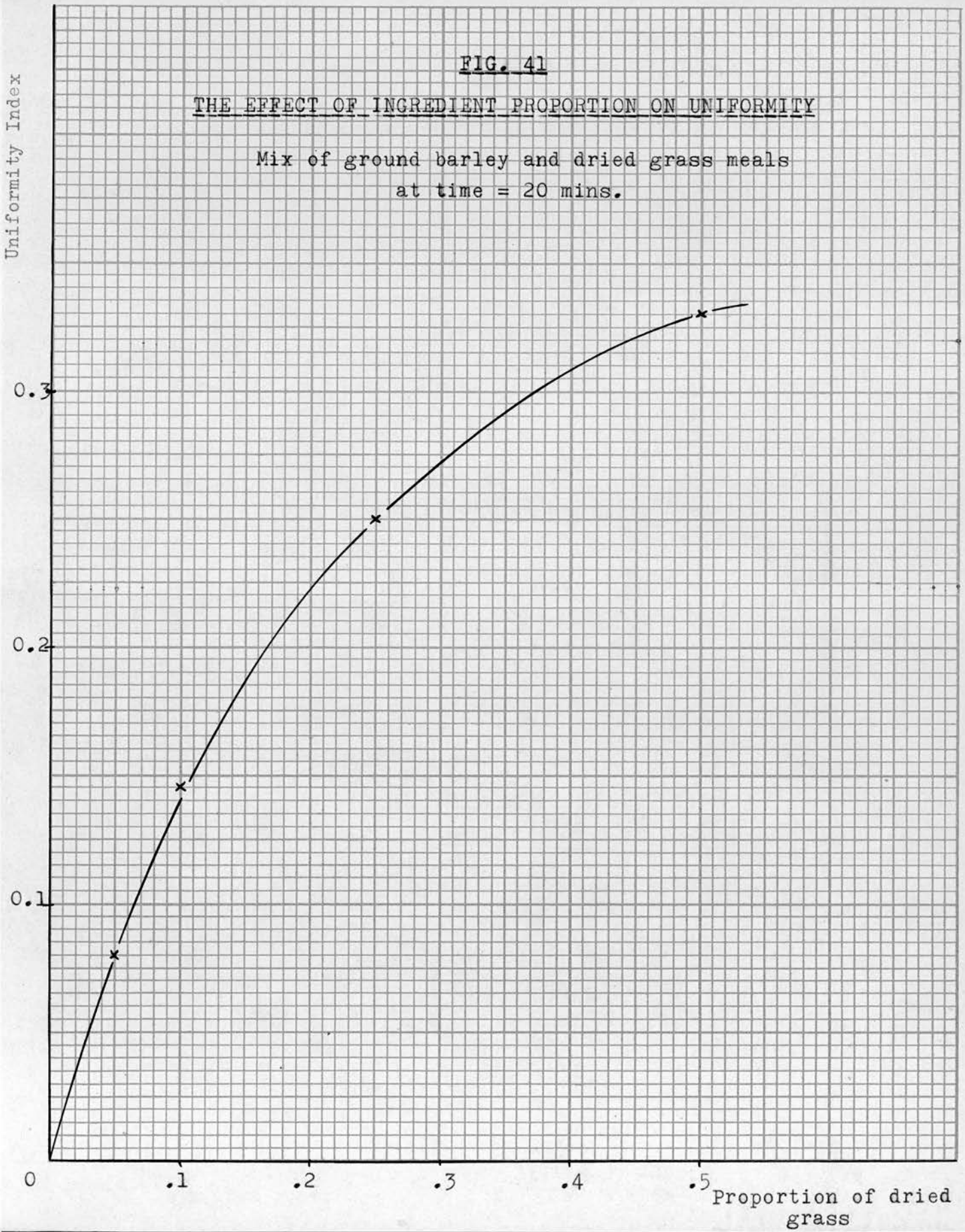
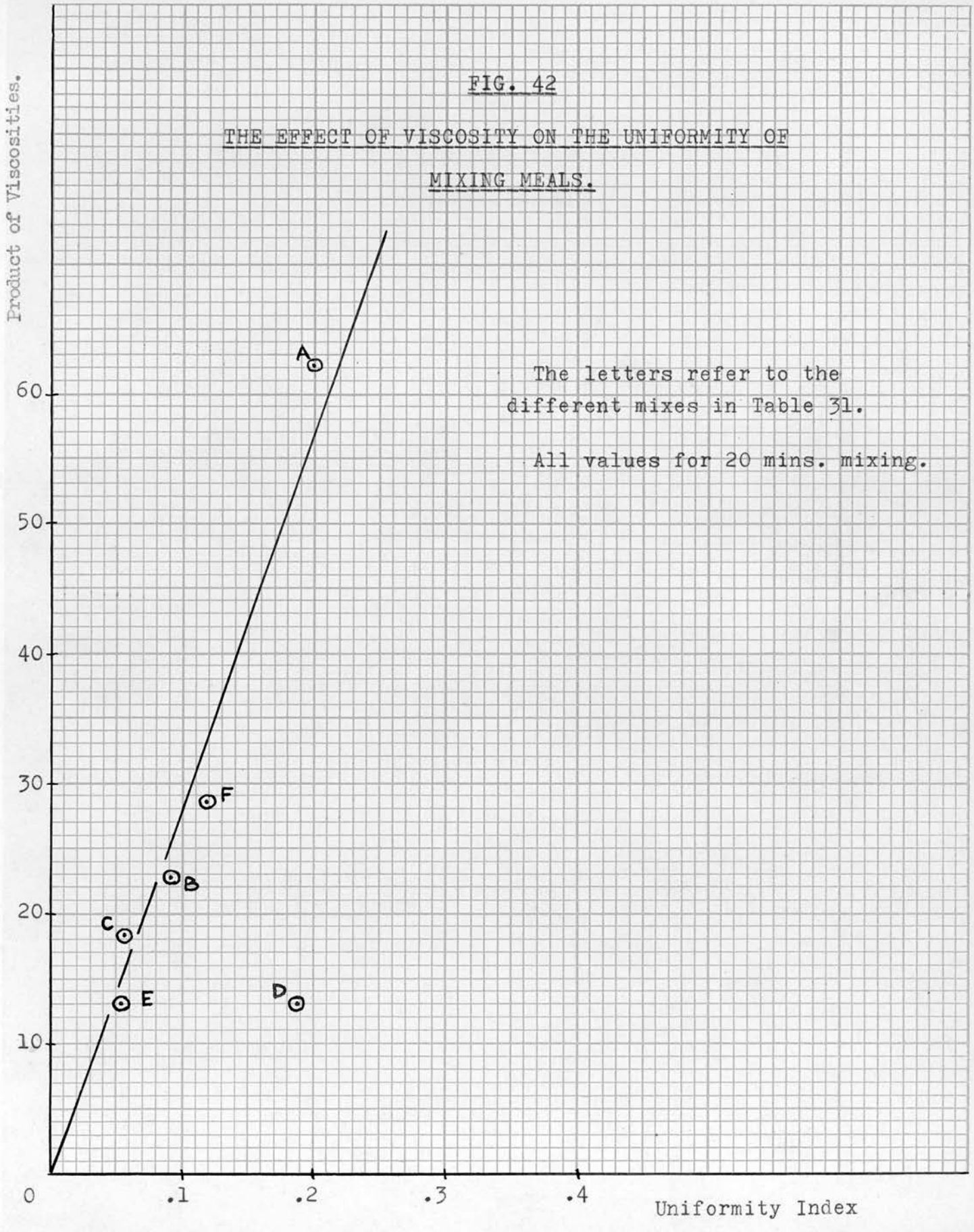


FIG. 42

THE EFFECT OF VISCOSITY ON THE UNIFORMITY OF MIXING MEALS.



Where S' and S" were the specific surfaces of the two components of a 20/80 mix and the U.I. was determined after 20 minutes mixing.

5.18 The effect of mixing more than two components.

The results in Table 22 from the mixing experiment with a 20/80 mix of skimmed milk powder and ground barley meal were plotted graphically in Fig. 34. An exponential curve was obtained for mixing time against U.I. determined by analysis of the barley fibre and the barley starch, whilst values of U_z were used to produce the mean curve. These results were obtained from three components of a mix by analysing two fractions of one meal, and it showed that each fraction of that heterogeneous meal behaved in a different way when mixed.

The barley fibre had attained a more uniform distribution after 5 minutes mixing than the barley starch had after 30 minutes; in the light of earlier experiments this was due probably to the smaller proportion of fibre.

The values of the U.I. for starch, fibre and barley as a whole are shown in Table 32.

TABLE. 32

Uniformity of a 20/19/61 mix of milk powder, barley fibre and garley starch.

Time	Uniformity Index.		
Mins.	Barley	Starch	Fibre
5	0.389	0.541	0.082
11	0.347	0.486	0.068
16	0.249	0.348	0.052
23	0.161	0.223	0.045
30	0.092	0.122	0.041

A further experiment was carried out with three components, the percentages and components of this mix were 1/10/89 butter salt, dried grass and ground barley meals. The U.I. of each component was obtained by analysis and recorded in Appendix A.29 and Table 33 along with the U.I. of the whole mix, U_z.

TABLE. 33

Uniformity of a 1/10/89 mix of salt, dried grass and barley meals.

Time Mins.	U_z	Uniformity Index. Salt	Dried Grass	Barley
10	0.321	0.055	0.208	0.513
20	0.195	0.040	0.152	0.300
30	0.118	0.057	0.129	0.149
40	0.081	0.068	0.095	0.082
50	0.068	0.101	0.058	0.033

The analyses used were Mohr's halide for the salt, chlorophyll extraction for the dried grass and iodine blue value for the starch fraction of the barley.

The interesting results in Fig. 43 showed the different rates of mixing for each component, the slowest being the barley meal and the rapidest the salt before it started to seperate. The mean curve for the whole mix showed that the greatest rate of mixing occured up to 30 minutes, after that it slowed down considerably and it was doubtful if the mix would achieve further uniformity after 50 minutes mixing. All the components had approximately the same U.I. after 40 minutes mixing and each value was less than 0.1. Once again the salt tended to seperate and its uniformity began to decrease with time after 20 minutes mixing.

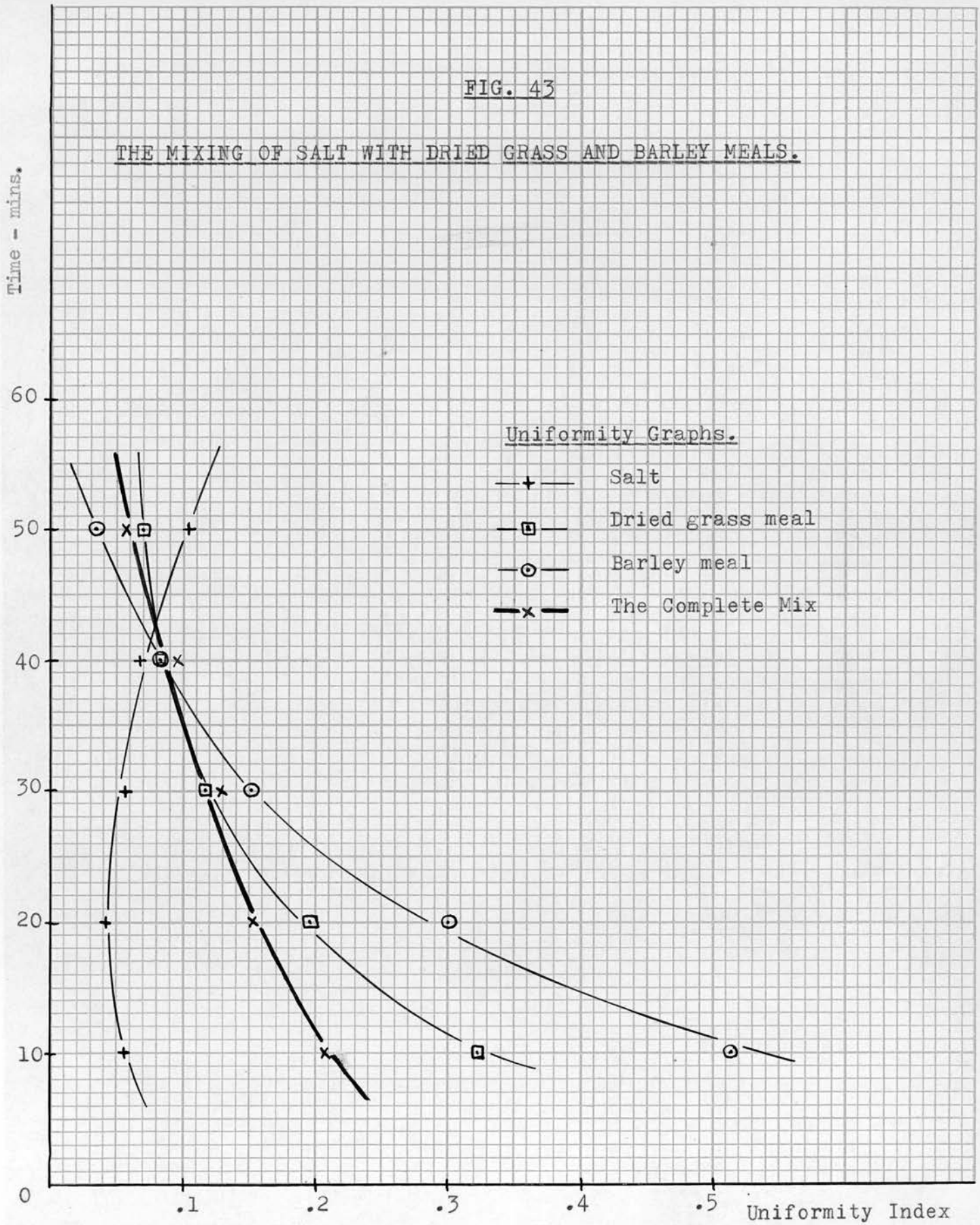
A further investigation was carried out with a complete poultry mix composed as follows:-

Coarse ground wheat ($\frac{1}{4}$")	27.0%
Fine ground oats ($\frac{1}{8}$")	25.0%
Fine wheat bran	15.0%
Dried grass meal	10.0%
White fish meal	10.0%
Skimmed milk powder	5.0%
Fine ground beans ($\frac{1}{8}$")	5.0%
Steamed bone flour	1.0%
Mineral supplement	1.0%
Vitamin supplement	0.5%
Butter salt	0.5%
	100.0%

Three samples were withdrawn after 35 minutes mixing from each of two mixes whilst they were being emptied from the mixer and the summarised

FIG. 43

THE MIXING OF SALT WITH DRIED GRASS AND BARLEY MEALS.



results are shown in Table 34 whilst the full analysis will be found in Appendix A.30.

TABLE. 34

Uniformity Analysis of a Poultry Food.

Chemical Components	True %	Sample Mean %	U.I.
Protein	16.4	16.65	0.026
Oil (ether extract)	4.3	4.37	0.005
Fibre	5.3	5.25	0.015
Nitrogen-free extracts	53.1	52.62	0.034
Mineral matter	8.8	8.68	0.025
Moisture	12.1	12.43	0.018
Total composition	100.0	100.00	0.022

Although the percentage of chemical components varied from 4.3 to 53.1 the U.I. was confined to a smaller range with rather less variation within it. The overall uniformity, U_z, was 0.022 which indicated that the mix was hardly uniform enough for feeding purposes, once again the observation was made that the smaller component proportions tended to reach a greater uniformity after a period of mixing.

5.19 The effect of feeding non-uniform mixes to animals.

The two rations fed to two groups of pigs were recorded in section 4.24; the non-uniform mix was planned so that each of the three components had a U.I. of approximately 0.011 and the overall uniformity as a consequence was the same, whilst its crude protein content deviated by 10% from that of the uniform mix. The results are listed in Table 35 and the complete analysis recorded in Appendix A.31.

TABLE. 35

The effect of a mix uniformity on Pig feeding.

Age	Uniform Mix Weight (lb.)		Non-uniform Mix Weight (lb.)		Variance ratio
Weeks	Mean	Total	Mean	Total	F
12	79.1	395.5	79.4	397.0	.002
13	87.5	437.5	87.7	438.4	.001
14	95.9	479.6	95.9	479.5	.000
15	104.5	522.4	103.9	519.3	.021
16	113.6	568.0	111.8	559.0	.098
17	122.1	610.6	119.0	594.9	.233
18	132.0	660.0	127.4	637.2	.461

For 4 and 5 degrees of freedom the the difference between treatments was insignificant at the 5% level, i.e. below F = 6.26.

The variance ratio was increasing with age of the pigs and the relationship produced a power equation of the form:-

$$t = .02F^{2.2}$$

where t was time in weeks and F the variance ratio obtained by statistical analysis.

This equation was used to find that the difference between treatments would be significant at the 5% level after 13.7 weeks and at the 1% level after 20.6 weeks.

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6. DISCUSSION OF THE RESULTS.

6.1 Examination of the properties of Meals.

The mean size of meal particles could be measured by microscophic measurement or by sieve analysis and the mean diameters, d_p, and d_l respectively, were related by the equation

$$d_p = 1.67 d_l$$

The results showed that sieving was not as reliable as microscophic measurement when assessing the mean diameter of particles. It would appear that elongated particles passed through sieve apertures longitudinally and were credited with a smaller mean diameter as a consequence. As was expected the specific surface, S, of particles increased as the mean diameter decreased and for barley meal it was proved that S was proportional to the reciprocal of d_p. Taking into account all the meals examined the relationships between S and the mean diameters were:-

$$S = 900 d_p^{0.87}$$

$$S = 1500 d_l^{0.81}$$

Sieving meals and examining the results emphacised the variable size and shape characters of the particles associated with mixing animal feeding stuffs. Mean diameters ranged from 3740 microns for flaked maize down to 32 microns for ground limestone; in general cereal meals, excluding flaked or crushed products, had a range of 245 to 1045 microns, non-cereal meals from 150 to 975 microns and minerals from 30 to 410 microns. The meals with smallest mean diameters had the smallest Fineness Moduli and they were classified more fully by studying the Uniformity Moduli too. Some meals were composed of only fine particles, but none were composed soley of medium or coarse particles. When a meal was made up of fine particles its F.M. lay between zero and 1.9, when it was mainly medium particles the F.M. was between 2.5 and 3.3 and when it was mainly coarse particles the F.M. range became 4.7 to 5.2. Obviously, throughout the whole range there were meals with two or three particle size groups in roughly the same proportions, but they could be identified generally by their different F.M. and U.M. values.

All meals used in feeding stuffs were derived by a size reduction process and the commonest was grinding, therefore it was interesting to examine the effect of the size of the grinding screen aperture on the mean diameter of the meal produced. It was found that the larger the aperture the coarser the meal and the relationship between aperture and particle mean diameter was represented by the equation for a parabolic curve. Cereals behaved similarly when ground, but milo meals had a smaller F.M. and bean meals a larger F.M. than cereal meals for given screen sizes.

Meals, being particulate, did not behave strictly as fluids under all circumstances, for example after pouring meal from a container it reposed in a heap. The angle of repose was a measure of the coefficient of friction between particles and for the meals examined the angle varied from 50° to 70°. The angle for a mixture of two meals was the same as the average for their individual angles and it was shown that it was necessary to have a slope angle steeper than 63° for meal mixtures to flow out of a hopper. Generally speaking meals with large specific surface or small particles had the greatest angles of repose and this could be explained from the fact that the coefficient of friction was a measure of the surface areas in contact. It had been thought that the viscosity of a meal could be measured by its angle of repose, but this was untrue because inter-particulate friction was only one of the factors affecting viscosity, the others were particle size, specific surface, meal density, moisture content and porosity.

Whereas particle shape factors had an effect on the degree of possible mixing between meals, kinematic viscosity, u_k, was a measure of the rate of mixing to reach that degree of uniformity. It was shown that pipe viscometers could be calibrated to obtain values of u_k for meals, the values obtained ranged from 1.1 cm^2/sec for ground limestone to 20.3 cm^2/sec for crushed oats. Viscosity tended to increase with increasing particle diameter and decreasing specific surface according to the approximate equations below:-

$$u_k = 2.4\, dp^{3/2} = \frac{S^{2/3}}{70}$$

Meals were less dense that the grains from which they were produced, but the apparent density of a meal was proportional to the true density of the grain in most cases. A low value for apparent density was brought about by increased voids, this was another factor which helped to explain why meals did not behave like true fluids. It was shown that the smaller the apparent density the more viscous the meal, which contradicted the results from the angle of repose examination. However, it could be suggested that the more dense particles produced a higher force of friction which resulted in a larger angle of repose, but when flowing down the viscometer their greater gravitational acceleration produced a shorter flow time and hence a low viscosity value. The density of ground cereal meals was constant for varying grinding screen aperture size.

When studying the effect of moisture content of wheat and barley meals on their viscosities a parabolic relationship was established that differed only slightly in magnitude for the two meals. The wheat meal appeared to be more free-flowing than the barley for any given moisture content and both flows were retarded similarly as the meal became more moist; the barley meal flow being retarded slightly faster than the wheat. These results tally with the common observation that damp meals tend to stick to conveyors and 'bridge' in bins or hoppers. Over the range of moisture contents investigated, 7% to 20%, the apparent density of the meals was unaffected by moisture.

The bulkiness of meals increased with increased particle size, increased specific surface and increased porosity and an approximate relationship between these factors was derived as follows:-

$$B = 6.6dp^{4/5} = \frac{3S}{400} = \frac{3}{80-P}$$

These inter-relationships could only indicate the trend in behaviour between B, dp, S and P because substitution of values for different meals gave slightly different results. This seemed to indicate that the different shape and size characteristics of particles within a meal produced different packing arrangements to those produced by materials broken down according to a regular pattern and tested by previous workers.

The examination of the properties of meals had shown that the mean diameter, specific surface, and coefficient of friction of particles and the apparent density, moisture content, porosity and kinematic viscosity of complete meals were related to a greater or lesser extent. The effect of these factors on the uniformity of mixing could be studied only during the mixing process.

6.2 The investigation of Mixer Design factors.

In order to study the mixing process it was necessary to construct an experimental mixer suitable for testing purposes; a model mixer was advisable to facilitate operation and to reduce constructional and material cost. It was convenient to choose a half-size scale and the model was designed accordingly.

The model was tested as a scaled-down version of a vertical auger-type mixer and it was determined that the mixing process in the model was representative of that in the full-size mixer when the respective Froude Numbers and centrifugal force factors remained constant. There was no need to maintain constant Reynold's Numbers and in this way the mixing of meals was likened to the mixing of liquids by previous workers. Observing these rules the mixing process in the half-size model represented that in an equivalent full-size mixer according to the following conversion equations:-

Length dimensions:	$L = 2 L_m$
Volume dimensions:	$L^3 = 8 L_m^3$
Mixing velocity:	$v = 2v_m$
Time of mixing:	$t = 2t_m$
Particle weight:	$w = w_m$

The model vertical auger-type mixer was used to investigate the effects of mixing time, mixer in-feed position, auger speed and design and mixing chamber size on the uniformity of mixing two meals together. Barley meal was used in combination with dried grass meal, skimmed milk powder or butter salt for this purpose.

The mixing process for meals was examined after different times and the

Uniformity Index determined by analysis of the samples withdrawn at each time. It was established that the U.I. was an exponential function of mixing time which agreed with Brothman's[31] supposition and the findings of Coulson[29]. The mixing equation had the following form:-

$$U.I. = ke^{ct}$$

The constants k and c represented, respectively, the degree of mixing at the start and the rate of mixing; their values were tabulated in Table 36 for the three basic binary mixes.

TABLE 36.

Values of the Mixing Constants.

Mix	k	c
50/50 Dried grass and barley.	0.42	0.56
20/80 Dried milk and barley.	0.80	0.75
1/99 Salt and barley.	0.12	1.48

These values showed that the salt/barley meal mix was least mixed at the start, probably due to the small amount of salt, but the rate of mixing was the quickest. It would appear also that the more alike the component proportions the slower the rate of mixing. After 30 minutes mixing the U.I. of the dried grass/barley meal mix was 0.242 whilst the milk powder/barley meal mix was twice as uniform and the salt/barley meal mix ten times as uniform. The last mix had been most uniform after 20 minutes too, but seperation occured after this time, the salt moving centrifugally to the mixing chamber sides, so that the mix became gradually less uniform. This phenomenum had been observed by Coulson and Maitra[29] when mixing chemicals.

The effect of the in-feed position on the uniformity of mixing was investigated with two mixes, 20/80 milk powder and barley meal and 10/90 dreid grass and barley meals, and both showed that the top-feed position produced a higher degree of mixing initially, but this advantage decreased with time. The results were rather surprising as it had been expected that the bottom-feed mixer would produce the greatest degree of mixing initially because the meals would be stirred during elevation from the feed hopper to the mixing chamber. This was not the

case in practice, it was suspected that there was better blending of the meals when they were tipped directly into the mixing chamber than when they followed one another up the bottom-feed cylinder. The different mixing curves of the mixes examined in this experiment again illustrated the variation in mixing rates for different mixes.

In the model mixer the motion of the meal particles was imparted by a vertical auger, therefore, its speed and design affected the rate of mixing whilst the type of mixing remained the same, namely, vertical elevation in the auger followed by radial dispersion and gravitational settling. There was an optimum auger speed for the two mixes studied, approximately 175 r.p.m. for the 20/80 milk powder and barley meal mix and 155 r.p.m. for the 1/99 salt and barley meal mix. It appeared that the higher speeds caused centrifugal seperation because their Uniformity Indices after 20 minutes mixing were greater than those for the optimum speeds; observations in the mixer discovered large barley particles in the centre and small powderlike particles at the outside. From these results it could be assumed that auger speeds would have no effect on mixes of particles with similar sizes and densities, but for heterogeneous mixes seperation would occur between particles of different sizes and/or densities; consequently, there would be a optimum speed for each mix and this appeared to be slower for the less viscous meals. Most incomplete mixing occured at the slowest speeds because insufficient energy was transferred to the meals to enable them to reach the sides of the mixing chamber. The optimum mixing auger speed should lie between a bottom limit that was just sufficient for particles to travel across the radius of the mixer and a top limit at which centrifugal seperation occured according to the different physical characters of the particles.

The design factors affecting the auger that were investigated were (1) fitting a cylindrical shroud around the upper part of the auger, and (2) fitting small spreading blades to the upper end of the auger. Both items improved mixing slightly and were considered worthwhile additions to this type of mixer

design. / The shrouded auger produced a 30% higher degree of mixing after 10 minutes that decreased with time to 15% after 30 minutes mixing, but in the case of the spreading blades the initial increase from fitting them was 12% and this decreased to 2% after 30 mins. mixing. In summing up it could be stated that there was a critical auger speed for each meal mix and that the rate of mixing could be increased by shrouding the auger and fitting spreading blades.

The shape and size of the mixing chamber affected the uniformity of mixing 20% skimmed milk powder and 80% barley meal in the model mixer with a fixed diameter of 22" and a hopper slope angle of 62°. Increasing the height of the parallel-sided part of the chamber increased its capacity but decreased the width/depth ratio and in doing so the uniformity after 20 mins. mixing was worse... The greatest degree of uniformity, under these conditions, appeared to be achieved when the width/depth ratio was about 1.5 i.e. when the depth was two-thirds the diameter.

Since each of the design factors had been investigated with a 20/80 mix of milk powder and barley meal, it could be established for this mix that the best mixing was attained when the meals were fed into the top of a mixing chamber that had a width/depth ratio of 1.5 and when the vertical auger was shrouded and fitted with spreading blades whilst rotating at a speed of 175 r.p.m. Under these conditions, the Uniformity Index after 20 mins. mixing would be 0.109 and after 45 minutes it would be 0.010 which represented the equivalent maximum value allowed by the Ministry of Agriculture requirements for animal feeding stuffs. The latter time represented a mixing period of nearly 64 mins. in a full-size mixer with twice the length dimensions of the experimental model; this was far in excess of the 15 - 20 mins. considered to be adequate by Summons[36].

6.3 The Investigation of Mix Composition Factors.

It was determined that the greater the difference between the component proportions of dried grass and barley meal in a mix the more rapid was that progress towards uniformity. Results showed that the U.I. was a parabolic function of the component proportions of this binary mix and the equation obtained after 20 mins. mixing was the following:-

$$U.I. = 0.033\, x^{0.63}$$

where x was the proportion of dried grass in the mix.

The work of Coulson and Maitra[29] contradicted the results obtained in this experiment, but the validity of the hypothesis that uniformity increased as the difference between component proportions increased was borne out by the parabolic curve in Fig.41. This curve passed through the origin and, therefore, the obvious conclusion was drawn that when the proportion of dried grass meal was nil the U.I. must be zero, in other words the mix was composed entirely of barley meal.

An analysis of the 20/80 mixes examined in the course of the experimental work indicated that the relationship between uniformity of mixing and viscosity of meals was a direct one involving the product of the kinematic viscosities of the components of a mix. The general equation developed was:-

$$U.I. = 1/3.u_k^{'}.u_k^{''}$$

where $u_k^{'}$ and $u_k^{''}$ were the kinematic viscosities of the two components. The value 1/3 would change probably for mixes of two components with percentage ratios other than 20/80.

The derived relationship between uniformity and viscosity proved that the other properties of meals, particle size, specific surface, density, moisture content, internal friction and porosity, also affected the uniformity of mixing. A general summary could be made saying that the U.I. would be smallest for the smallest product of kinematic viscosities, i.e. less viscous mix components, and consequently, the U.I. of a mix could be reduced by increasing the apparent density and decreasing the moisture content, porosity, particle size and specific surface of the meals. This data should be useful in establishing the mixability of different meals and hence the time of mixing for the greatest degree of uniformity.

The effect of mixing more than two components was explored with a simple mix containing salt, dried grass and barley meals following the examination of the behaviour of the starch and fibre fractions of barley meal. Each component

followed an exponential equation for increasing uniformity with increasing time but at different rates. This meant that the U.I. at any time for the whole mix was a function of the U.I. of all components and the factor, U_z, derived in section 2.24 provided a satisfactory relationship in practice.

$$U_z = \left(\frac{U^2}{N}\right)^{\frac{1}{2}}$$

Since the value of a feeding stuff depended upon its chemical composition, i.e. protein, starch, fibre etc., rather than the actual proportion of each component, it was considered a wise thing to study the uniformity of a mix on this basis. A complete poultry meal was chosen and mixed for 35 minutes in a full-size 10 cwt. mixer and the U.I. for the whole mix was found to be 0.022. This could not be called satisfactory in view of the fact that a special non-uniform mix with the maximum deviation of 10% protein permitted by the Ministry of Agriculture had a U_2 value of 0.011. This non-uniform mix was fed to a group of pigs and their weights were compared with those of a group fed with a completely uniform mix; the results showed that the difference in weight was not significant at the 1% level until after 20 weeks feeding. Since this was longer than pigs would be fed for pork or bacon purposes it was concluded that the Ministry of Agriculture regulations allowed a sufficiently large safety margin.

The alarming pointer that arose from this experimental work was the fact that no mix had a U.I. of less than 0.020 and this seemed to indicate that either the time of mixing was insufficient or the design of the vertical auger-type mixer was inadequate. The time for a sufficiently uniform mix could be obtained from the mixing curves, but any improvements in the mixer design might be limited by the fact that it was impossible to attain 100% uniformity with some of the mixes no matter how long the mixing time.

7. CONCLUSIONS.

This thesis was produced as a result of a fundamental study of the mixing of feeding stuffs with special reference to their uniformity and the more important findings have been abstracted in the following ten paragraphs.

1. The mixing process was studied in a vertical auger-type meal mixer by sampling the uniformity of the mix after definite periods of time. The testing of a half-size mixer proved that the mixing process could be scaled down for study experimentally, provided that the scale factors were recognised, particularly the Froude Number and the centrifugal force and time factors. The use of scale meals was unnecessary.

2. The mixing equation was exponential and based on the time to reach uniformity, its form being:-

$$U.I. = ke^{ct}$$

The constants indicated the initial degree of mixing and the rate of mixing respectively, whilst the equation showed that the rate of producing uniformity in a mix decreased with time.

3. The uniformity of a mix was represented statistically by the Uniformity Index which was a measure of the deviation of mix samples from the desired uniformity. The index for the complete mix was obtained from the variance of the Indices for the individual mix components. The uniformity of mixing was affected by two groups of factors; (1) the physical properties of the meals and the composition of the mix; and (2) the design factors of the mixer and the operation of the mixing process.

4. The physical properties of meals affected the mixing process and viscosity was the most important. Kinematic viscosity of meals was assessed satisfactorily with a calibrated pipe viscometer and was found to be a function of particle size, specific surface, apparent density, porosity, moisture content and internal friction of meals. The greater the viscosity of meals the longer time required to mix them uniformly, therefore, those properties related to kinematic viscosity would determine the 'mixability' of meals; mixing would be least difficult for components with the smallest particle size, specific surface, porosity, angle of repose and moisture content, but greatest apparent density. The fine particled meals

behaved most closely as fluids, possibly because of electrical attraction between particles or because of less resistance to the air medium.

5. The composition of the mix varied according to the proportions of the components and the number of components. An increase in the difference between two mix components gave a parabolic increase to the mix uniformity, so that a zero Uniformity Index was attained when the mix was composed entirely of one component. The fact that components with small mix proportions tended to reach uniformity more quickly was borne out by experiments with small dried grass meal and salt proportions in a barley meal matrix and by analysis of barley fibre and starch. When examining the mixing of a poultry food by analysing its chemical composition it was found that the Uniformity Index after 35 minutes mixing in the full-size mixer was 0.022 which showed that its uniformity was insufficient for normal feeding purposes when compared with the Index of 0.011 for a mix 10% deficient in protein. The uniformity of complex mixes depended upon the degree of dispersion of each component and so the poor dispersion of one component adversely affected the uniformity of the mix as a whole.

6. The mixer design features investigated with the model vertical mixer included in-feed position, different mixing chamber sizes and different speeds and conformations of the mixing auger. The results showed that a 20/80 mix of milk powder and barley meal would attain the greatest degree of uniformity when mixed in the top-feed version of the mixer, with a mixing chamber whose depth was two thirds its diameter and when the mixing auger was shrouded, fitted with spreading blades and rotating at 175 r.p.m. The speed of an equivalent full-size mixer would be 250 r.p.m.

7. The mixing time varied according to the mixing equations for each mix, the times for satisfactory uniformity varying from 40 minutes to 100 minutes. however, mixes containing salt could never attain complete uniformity because it tended to separate after approximately 20 minutes mixing. The time to reach a given uniformity increased with the number of the ingredients and the increased product of their kinematic viscosities.

8. The best Uniformity Index recorded during any experiment was 0.02,

a value that was not up to expectation. Seperation was a limiting factor in some cases, but excluding this factor it appeared that either the mixing times were too short, or that the design of the mixer was unsuitable. It was possible that uniformity would be improved by modifying the technique of feeding the ingredients into the mixer; for example in-feeding the slow moving ingredients first and then the faster ones according to their kinematic viscosities or mixing rates.

9. Feeding a non-uniform mix to pigs indicated that it retarded the rate of growth when compared with a completely uniform mix over a period of six weeks. the non-uniform mix was 10% deficient in protein, being the maximum allowed by the Ministry of Agriculture regulations, and it was estimated that it would not have a highly significant effect on the growth rate until after 20 weeks feeding which was longer than the type of mix chosen would be fed in practice.

10. The complete study had helped to clarify the factors tnat influenced the mixing of feeding stuffs and to establish the importance of time and certain mix composition and mixer design factors on the uniformity of mixing. Mixing was shown to be a complicated process, but it was hoped that the results from the fundamental principles investigated would serve in some way to improve feeding standards.

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A P P E N D I X

A.1. Particle shape characteristics.

TABLE I.

Volume coefficient, C, for angular particles (C_e = 0.431)

Elongation n	Flakiness, h. 1.0	1.2	1.5	2.0	2.5	3.0
1.0	0.43	0.36	0.29	0.22	0.17	0.14
1.2	0.39	0.33	0.26	0.20	0.16	0.13
1.5	0.35	0.29	0.23	0.18	0.14	0.12
2.0	0.30	0.26	0.20	0.16	0.12	0.10
2.5	0.27	0.23	0.18	0.14	0.11	0.09
3.0	0.25	0.21	0.17	0.12	0.10	0.08

TABLE II.

Surface coefficient, f, for angular particles.

Elongation n	Flakiness, h. 1.0	1.2	1.5	2.0	2.5	3.0
1.0	3.58	3.16	2.75	2.30	2.16	2.03
1.2	3.41	3.03	2.64	2.31	2.12	2.00
1.5	3.25	2.89	2.54	2.24	2.07	1.96
2.0	3.08	2.77	2.45	2.18	2.01	1.92
2.5	2.98	2.68	2.39	2.14	1.99	1.89
3.0	2.91	2.63	2.36	2.10	1.97	1.88

TABLE III.

Values of $\frac{dp}{A}$ for angular particles.

Elongation n	Flakiness, h. 1.0	1.2	1.5	2.0	2.5	3.0
1.0	1.00	1.06	1.14	1.23	1.28	1.32
1.2	1.09	1.17	1.25	1.35	1.41	1.44
1.5	1.22	1.30	1.39	1.51	1.57	1.61
2.0	1.41	1.51	1.61	1.74	1.82	1.87
2.5	1.57	1.68	1.80	1.95	2.03	2.08
3.0	1.73	1.84	1.97	2.13	2.23	2.28

Underlined figures represent more usual mineral particle proportions, the average value for such materials was 1.43

A.2. Meal Sampling Techniques.

The weights for ten samples of barley meal taken with the sampling spear from a meal bin were 115.1, 119.8, 145.3, 133.0, 110.9, 132.2, 148.2,

136.6, 128.0 and 130.0 grams respectively. These figures gave an average weight of 129.9 gm., variance of 130.1 and standard deviation of 11.4 gm.

Differences	t	D.F.	P
Spear and Flow methods	0.417	8	0.71
Spear and Sack methods	0.088	8	0.93

A.3 Chlorophyll Extraction from Dried Grass.

It was decided to add 5 lb. of dried grass meal to standard animal feeding stuff mixes used on the University farms. The batch size was 10 cwt., thus 5 lb. represented one part in 260 and if the batch was uniformly mixed and 1 lb. sample should contain $\frac{1}{260}$ lb. or 1.67 gm. dried grass. This size of sample was chosen for the N.I.A.E. Test Procedure for Farm Mixers [46] as a comprise between the 4-10 lb. helping for a cow and the few ounces fed to poultry.

The chlorophyll extracted from 1.67 gm. dried grass was diluted with 250 ml petrol ether in order to obtain deflection on the scale of an E.E.L. Colorimeter. The deflection for a range of dilutions is shown in the following table and the calibration graph in Fig. 44.

Colorimetric estimation of chlorophyll.

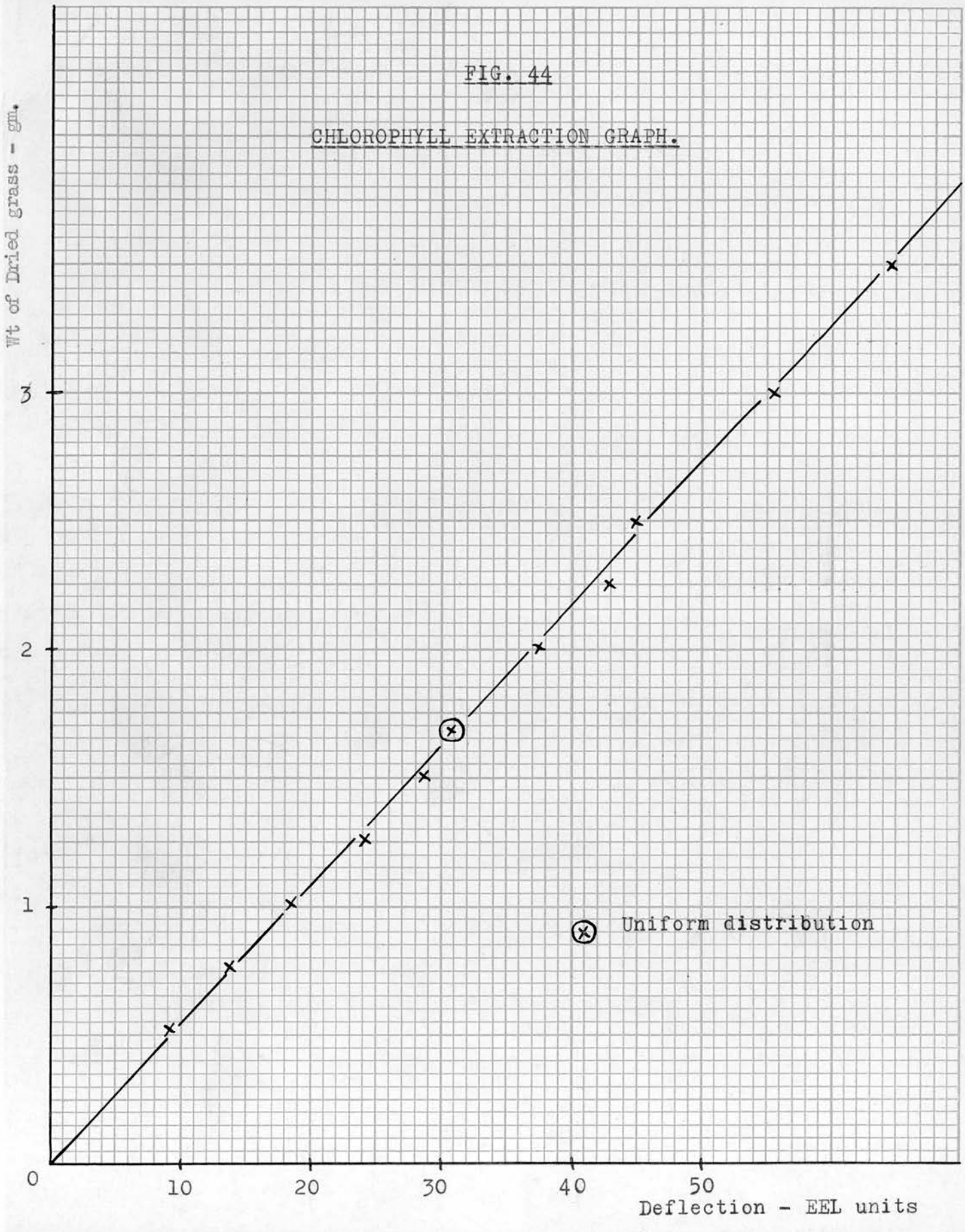
Wt. of Dried Grass gm.	Deflection with Filter. 604
0.5	8.8
0.75	13.3
1.0	18.1
1.25	23.6
1.5	28.3
1.67	30.5
1.75	32.7
2.0	37.0
2.25	42.1
2.5	44.7
3.0	55.0
3.5	64.1

Test with Standard Mixes.

5 lb. dried grass meal was added to Mixes A and B which are being

FIG. 44

CHLOROPHYLL EXTRACTION GRAPH.



compounded at Seafield Foodstore and two lb. samples were drawn after 5, 10, 15 and 20 minutes mixing. They were diluted as in the previous test. The results are given in the Table below:

Mix A.	Mix B.
20% Milo Meal	40% Barley meal
20% Barley meal	20% Groundnut cake
25% Oat meal	15% Soyabean meal
7% Soyabean meal	20% Oat meal
5% Fishmeal	3% Yeast
20% Groundnut cake	1% Limestone
2% S.B.F.	1% Minerals
1% Minerals	100%
100%	

5 lb. Dried grass was added to each 10 cwt. mix.

Results of estimating dried grass in Mixes A and B.

Time in min.	Deflection	Wt. of Dried Grass	Deviation From Mean	Deflection	Wt of dried Grass	Deviation From Mean
5 min	10.2	0.65g.	1.02g.	4.5	0.24g.	1.43g.
	30.5	1.67g.	0.00g.	27.1	1.53g.	0.14g.
10 min	20.1	1.12g.	0.55g.	26.3	1.43g.	0.24g.
	38.0	2.17g.	0.50g.	36.7	2.02g.	0.35g.
15 min	29.7	1.62g.	0.05g.	31.3	1.72g.	0.05g.
	35.3	1.93g.	0.26g.	18.5	1.02g.	0.65g.
20 min	28.9	1.58g.	0.09g.	30.1	1.65g.	0.02g.
	31.3	1.72g.	0.05g.	36.6	1.94g.	0.27g.

This small trial showed that the dried grass tended to become more uniformly mixed as time proceeded, but it was difficult to say whether it blended more readily in either Mix. A or Mix. B.

A.4 Analysis for Salt and Barley Meal Mixtures.

The analysis was based on Mohr's method of estimating halides and recorded by Lowry and Cavell [49]. For the model mixer the 30 gram sample of 1% salt and 99% barley meal mixture was shaken vigorously with 100 ml. de-ionised water. It was stirred twice during a 30 minute waiting period and then filtered through a coarse Whatman paper (No. 54) in a Buchner

funnel into a flask connected to a vacuum pump. The residue was washed with an additional 50 ml. of water and the whole filtrate titrated against a standard silver nitrate solution in the presence of 1 ml. potassium chromate as indicator. The silver nitrate was standardised so that 40 ml. neutralised 1 gm. Cl. shaking was necessary to obtain the red-brick colour of silver chromate as the end-point.

Tests were carried out with salt alone, barley meal alone, and artificially uniform mixtures of the two. The amount of Cl. extracted from the meal was negligible, in fact some was taken up in the mixture as the recovery for the mixture was 90%. It was considered a satisfactory analysis for tracing the salt in a meal mixture.

	$AgNO_3$ ml.	Cl. gm
Salt	6.7	0.168
	6.7	0.168
Barley meal	0.6	0.015
	0.5	0.012
1-99 mixture	6.2	0.155
of salt and	5.8	0.145
barley meal	6.0	0.150

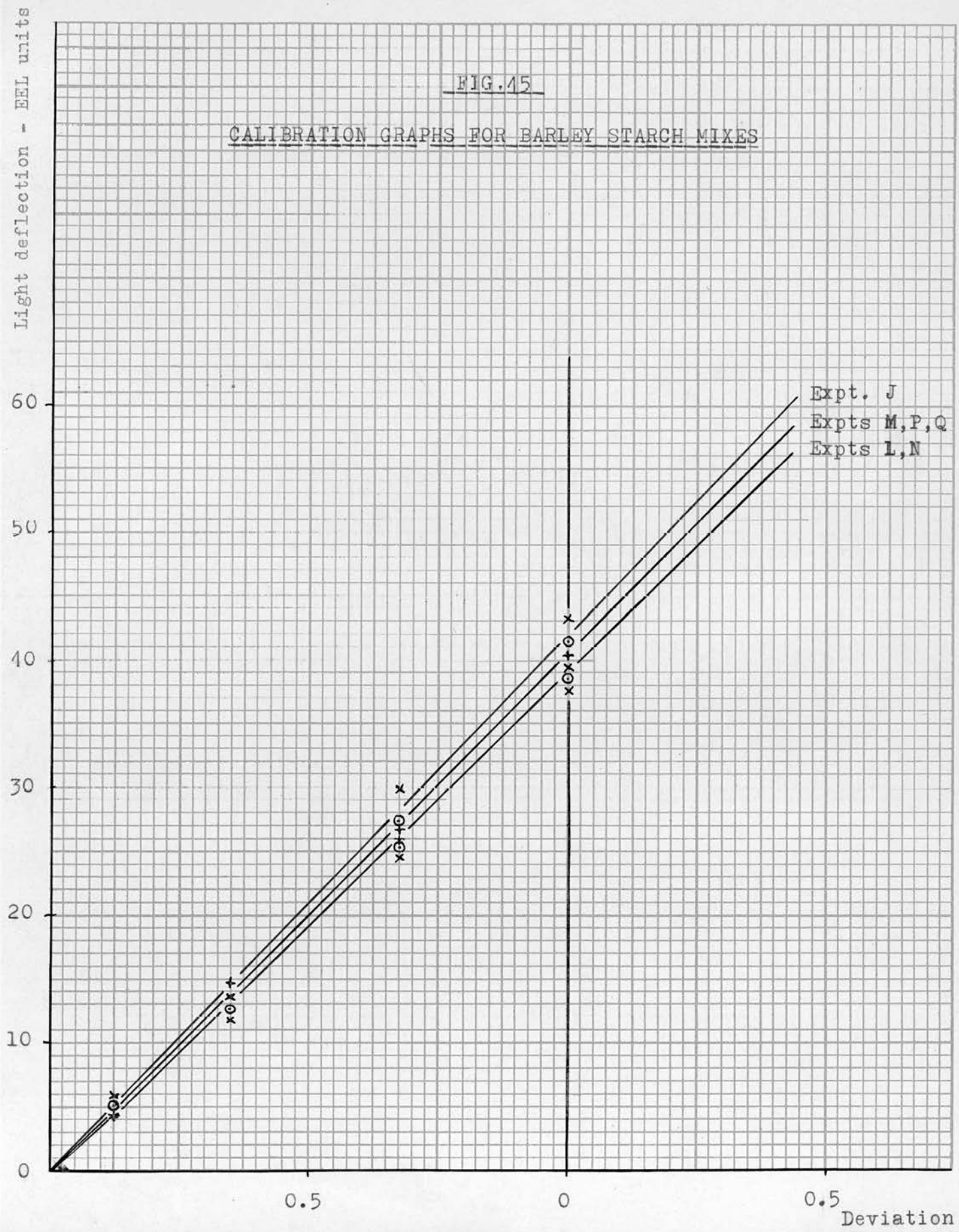
A.5 The Analysis of Starch in Meals.

Reference was made to the Iodine Blue Value by Bourne[50] for estimating starch and the method was adapted by McDonald[51] so that the intensity of the blue colour could be measured in the E.E.L. absorptiometer. A series of starch solutions ranging in concentration from 0.1 mg. to 1.0 mg. per ml. were made up and to them were added 5 ml. of 0.0025 N Iodine solution (diluted from an O.I.N. starch solution containing 20 g K I and 12.7 I per litre). The colour was measured in the absorptioneter using a red filter No. 205 and the straight line graphs produced are shown in Fig.45.

This method was ideally suited to tracing a meal containing starch in the presence of animal products that did not. The actual weight of starch present could only be obtained from comparison with the Blue Value of the pure starch alone. This meant obtaining pure starch from each of the meals, only wheat and maize starches were available unfortunately, and they could be traced if

FIG.15

CALIBRATION GRAPHS FOR BARLEY STARCH MIXES



more that one starchy meal was present. Consequently, a standard test was performed with known proportions of barley meal and milk powder and the actual amounts present in the mix based on percentage deviations from the standard.

A6. Estimation of Lactose in Skimmed milk.

The analysis for skimmed milk was based on an estimation of the quantity of reducing sugar present - namely lactose. The amount of reducing sugars present in barley was very small, consequently the test could be used specifically for tracing the skimmed milk powder in the presence of barley meal.

The method used was as follows. A 4 gm. sample was placed into a 200 ml. conical flask along with 5 ml. each of Zinc acetate and potassium ferrocyanide reagents and made up to 200 ml. with distilled water. The flask was then shaken vigorously before filtering into a dry beaker. 25 ml. of the filtrate was pipetted into a stoppered conical flask and two drops of phenolphthaleine added. It was then neutralised with approximately 0.1N soda and an additional 3 ml. added, in addition a blank titration was carried out with 25 ml. water plus 3 ml. soda.

Now 50 ml. of 0.05N chloramine-T and 10 ml. of 20% KI solution were added, these were not standardised because of the blank test. The flask was left for 90 minutes in the dark before adding 10 ml. dilute HCl and titrating against 0.1 N 'hypo'. The amount used to turn the solution colourless was directly proportional to the amount of reducing sugar present in the original sample.

Shaking the sample with warm water instead of cold gave a lower resultant value for the lactose.

	Sample weight gm.	Hypo volume ml.	% Reducing Sugar
Skimmed milk	3.922	13.06	47.17
in cold water	3.983	13.55	48.19
Skimmed milk	3.945	12.19	43.77
in warm water	3.998	12.47	44.18
¼" ground barley	3.991	0.26	0.93
	4.007	0.21	0.74

When the mixing experiments were being carried out several months later the % of reducing sugars for the barley had increased considerably due to hydroysis during storage. The new values are given below.

Meal	Sample wt. gm.	Hypo volume ml.	Reducing sugar %
Skimmed milk	3.979	13.66	44.08
	3.994	13.85	49.60
Barley meal	3.943	1.13	7.44
	4.005	1.06	6.96

Due to the large proportion of barley meal in the mix it would give about the same reaction as the milk powder to the test, which had to be discarded as a consequence.

A7. Comminution of Flaked Maize during mixing.

The use of coarse grained materials as tracers was suggested in Section 4.4 (part 7), consequently a trial run with a 50-50 mixture of flaked maize and fine ground barley was carried out in the full-size mixer. The mixing time was 20 minutes - the manufacturer's recommended time. Only the coarse fraction of the maize was used (screen 16 and above) and the medium and coarse fractions of the barley (below screen 16). These two groups were expressed as percentages of the sample drawn.

Sample	% coarse	% fines	Increase in fines
Original mixture	50	50	-
After mixing (mean of 12 sample)	36	64	14%

The increase in fines seemed very large and it was assumed that the random sampling had eliminated any anomaly due to non-uniform mixing. Therefore a test was carried out with flaked maize alone. Samples were drawn from the top and bottom of the mixing chamber and from the bottom of the infeed portion of the auger.

Sampling Position	F.M.	% change
Original flaked maize	5.26	-
Mixing chamber - top	5.39	+ 2.47
- bottom	4.60	- 12.55
Infeed auger	4.21	- 19.96
Combined mixed samples	4.47	- 15.02

This test proved that comminution of the flaked maize occured during mixing and that the finer material was sifted to the bottom of the mixer.

A8. Cellulose Analysis.

A modification of the Crampton and Maynard[54] method was used. A 4 gm. sample was placed in a 150 ml. flask fitted with a reflex condenser, 15 ml. 80% acetic acid and 1.5 ml. nitric acid were added and the mixture boiled for 20 minutes to dissolve all material except the cellulose. After cooling 20 ml. alcohol was added and the mixture filtered under vacuum through an asbestos lined crucible. The residue was washed free of acid with alcohol and dried at 100°C before weighing and igniting. The loss of weight after ignition represented the cellulose.

Meal	Wt. lost gm.	Cellulose %
Skimmed milk powder	.0000	-
¼" ground barley	.2038	5.92
Broad wheat bran	.3497	10.15

Due to the exacting nature of this test the simpler and less critical method of Walker and Hepburn[55] was adopted instead.

A 4 gm. sample was milled through a 1 mm. screen and placed into a one litre flask with exactly 500 ml. of water and brought to the boil with a reflex condenser. Boiling for 10 minutes dissolved the starch and 10 ml. of the liquor was removed for the starch anaysis. The rest was made up to normal acid standard by the addition of the appropriate quantity of concentrated sulphuric acid. The meal was digested for an hour before

filtering through a Whatman 54 paper using a vacuum pump, finally washing free of acid with alchohol. The residue was dried to constant weight and weigh weighed. It was then ashed for 30 mins. at 600°C and weighed again; the difference in wieght was termed Normal Acid Fibre, being composed of both cellulose and lignin.

A9. Viscosity tests with Conical flask Viscometer.

Flask angle = 67½°

Diameter of orifice = 20 mm.

Volume of flask = 300 ml.

Rate of flow = time to empty recorded in seconds with a stop-watch.

Meal	Time (secs)		
¼" ground beans	6.5	6.4	6.6
¼" ground oats		no flow	
¼" ground milo	7.4	7.4	7.6
Soya bean meal	3.5	3.5	3.5
Steam bone flour	14.5	16.0	16.5
Wheat bran		no flow	
Milk powder	5.5	5.0	6.5
¼" ground barley	3.5	4.0	4.0
Dried grass meal		no flow	
Flaked maize		no flow	
Butter salt		no flow	

A10. Calibration of Pipe Viscometers.

Volume of small pipe = 415 ml.

Volume of large pipe = 1870 ml.

Ratio of volumes = 4.51

Ratio of internal surfaces = 9.71

Temp. °C	Temp. °F	Viscosity of Water (Jameson[56]) u	p	$u_k = u/p$
0	32	.001205	62.42	.0000193
10	50	.000880	62.41	.0000141
20	68	.000676	62.32	.0000104
30	86	.000538	62.16	.0000086
40	104	.000442	61.94	.0000071
50	122	.000370	61.68	.0000060
60	140	.000315	61.38	.0000051
70	158	.000273	61.04	.0000045
80	176	.000240	60.67	.0000040
90	194	.000213	60.26	.0000035
100	212	.000191	59.83	.0000032

Jameson's table is given in absolute ft. lb./sec. units and these need to be converted to c.g.s. units to comple with the experimental viscometry results. They are given in the table below.

Viscosity of water in c.g.s. units

Temp. °C	u centipoise	u_k cm^2/sec
0	1.777	1.785
10	1.508	1.511
20	1.001	1.065
30	0.797	0.804
40	0.653	0.656
50	0.546	0.553
60	0.468	0.476
70	0.405	0.415
80	0.355	0.365
90	0.314	0.329
100	0.281	0.294

It was difficult to control the water temperature precisely when calibrating the viscometers, therefore values of u_k were needed for the

full range of water temperatures. These were obtained by plotting the graph of temperature against viscosity and is given in Fig.46.

Each viscometer was calibrated in turn by filling with water at various temperatures and the time for emptying was recorded for each test. The actual results are given in succeeding pages and the graphs of time against viscosity as each temperature are shown in Figs.47 and 48. Extra meal tests were carried out with the large pipe viscometer to test the validity of these calibration equations.

Results of water calibration of pipe viscometers.

Temp	Small Pipe		Large Pipe	
^{o}C	$\frac{u}{k}$ cm^2/sec	t sec.	$\frac{u}{k}$ cm^2/sec	t sec
15	1.250	1.5	-	-
		1.5		
		1.4		
		1.5		
		1.5		
25	-	-	0.912	3.7
				3.9
				3.6
				3.4
				3.9
27	0.868	1.3	-	-
		1.2		
		1.2		
		1.3		
		-		
35	0.720	1.2	0.720	2.5
		1.1		2.8
		1.2		2.8
		1.1		2.6
		-		-
45	0.600	1.0	0.600	1.8
		0.9		2.0
		1.0		1.9
		1.1		2.1
		1.0		2.0
50	0.553	1.0	0.553	1.8
		1.0		1.7
		1.0		1.8
		1.0		1.8
		-		-

Temp	Small Pipe		Large Pipe	
^{o}C	cm^2/sec u_k	sec.	cm^2/sec u_k	t sec
55	0.506	0.8	-	-
		1.0		
		0.9		
		0.8		
		-		
65	0.438	1.0	0.438	1.0
		1.0		1.4
		0.8		1.3
		0.84		1.4
		0.9		1.1
95	0.310	0.7	-	-
		0.6		
		0.6		
		0.8		
		0.9		

Small pipe Calibration.

The curve for the mean time - viscosity values for water was a straight line, which cut the y axis at - 0.91 and had a slope of tan Θ = 1.79, as shown in Fig.47. This meant that the calibration equation was

$$u_k = 1.79t - 0.91$$

The fastest rates of flow gave the greatest scatter of times due to the smaller margin of error available for the timing mechanism, consequently, most emphasis was placed on the slower flow values. The value of the constant 'a' had to be obtained by extrapolation.

Large Pipe Calibration.

Similar results were obtained for the large pipe, but due to its size and difficulty in maintaining the temperature of larger volumes of water for longer times the number of readings was reduced. However, a satisfactory straight line graph resulted; the calibration equation being obtained from Fig.48 as follows.

$$u_k = 0.23 + 0.45t$$

A few test runs with different meals gave a very good corelation between these two equations thus proving their validity under these experimental conditions.

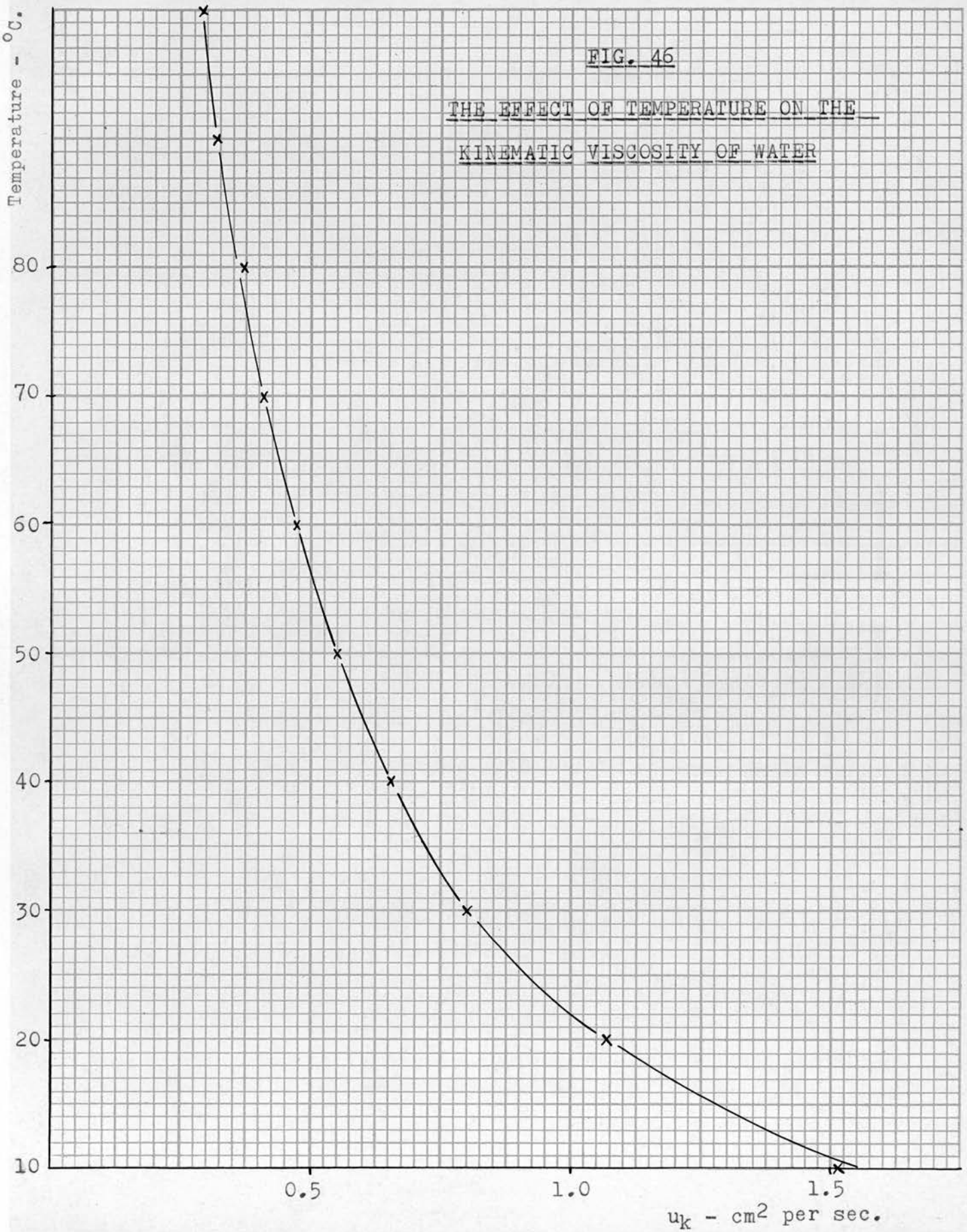
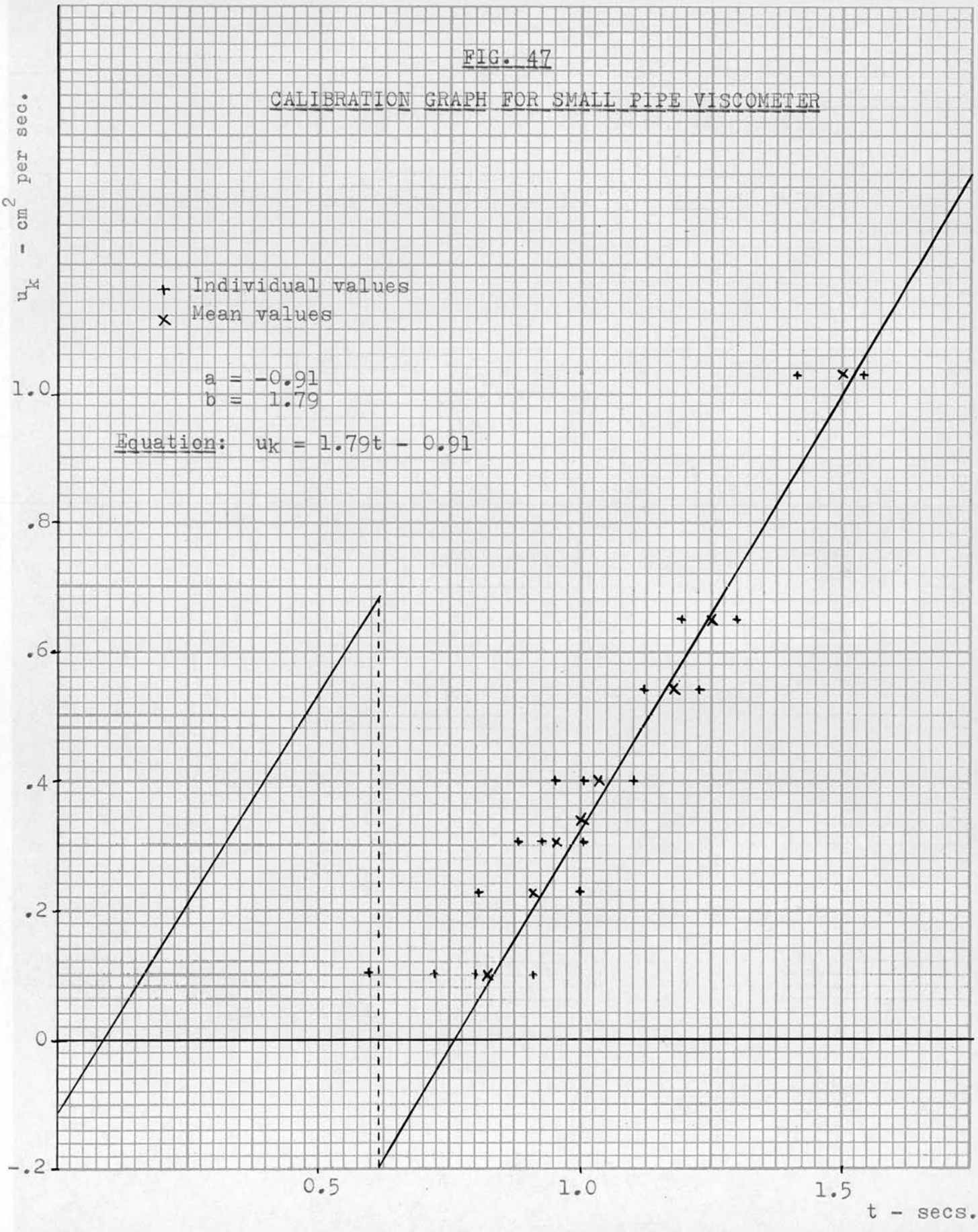


FIG. 46
THE EFFECT OF TEMPERATURE ON THE KINEMATIC VISCOSITY OF WATER
Temperature - °C.
80
70
60
50
40
30
20
10
0.5
1.0
1.5
u_k - cm² per sec.

FIG. 47

CALIBRATION GRAPH FOR SMALL PIPE VISCOMETER



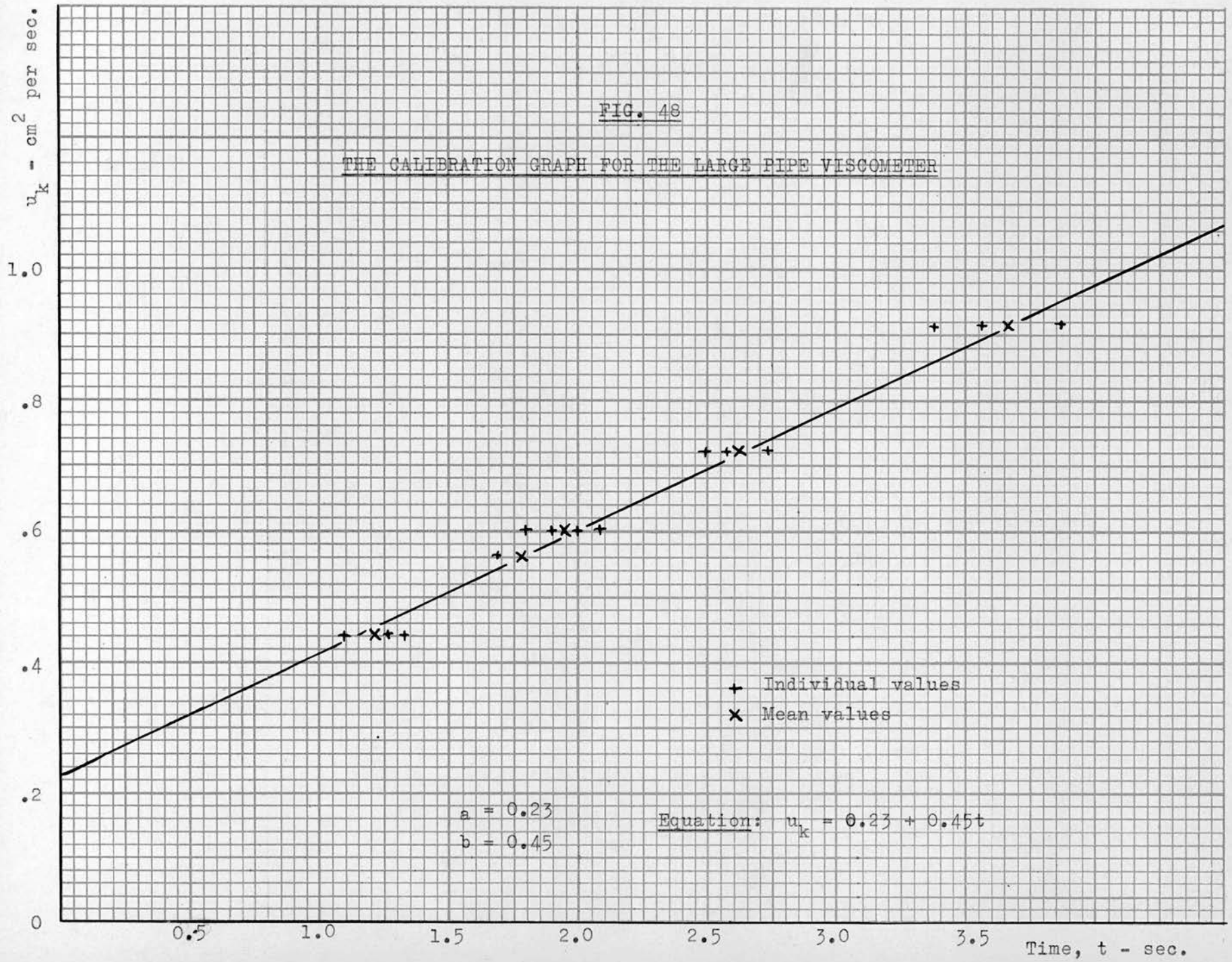


FIG. 48
THE CALIBRATION GRAPH FOR THE LARGE PIPE VISCOMETER
u_k - cm^2 per sec.
1.0
.8
.6
.4
.2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Time, t - sec.
+ Individual values
× Mean values
a = 0.23
b = 0.45
Equation: $u_k = 0.23 + 0.45t$

Conclusions.

The straight pipe viscometers devised for measuring the kinematic viscosity of meals were quite suitable for the purpose; especially as the relative viscosities ~~(mainly)~~ were required for comparing the mixability of meals. It appears that any pipe diameter can be used provided the oriface is constant and of sufficient size to allow the free passage of meals.

Confirmation tests with meals in the large Viscometer.

Meal	wt. gm	t sec	Marconi Units mc.
⅛" ground wheat	1080	5.0	
	1075	4.6	34
	1080	3.8	
	1085	5.0	14.5%
	1080	4.8	
⅛" ground milo	1227	3.6	
	1222	3.8	
	1224	3.5	30
	1225	3.2	14.4%
	1230	3.5	
3/16" ground barley	1028	10.5	
	1066	11.2	32.5
	1028	11.4	
	1056	9.9	14.1%
	1064	11.1	
¼" ground beans	1260	7.6	
	1274	7.8	36.5
	1279	7.8	
	1274	7.9	14.4%
	1276	7.9	

Comparison of Large and Small Viscometers.

Meal	Small Pipe t sec	Small Pipe ν_k cm^2/sec	Large Pipe t sec	Large Pipe ν_k cm^2/sec
⅛" ground wheat	1.8	2.30	4.6	2.30
⅛" ground milo	1.6	1.95	3.5	1.81
3/16" ground barley	3.7	5.71	10.8	5.09
¼" ground beans	2.6	3.74	7.8	3.74

All. Estimation of Uniformity when mixing Dried Grass.

The quantity of meal containing dried grass was weighed into a paper thimble and placed into a soxhlet extractor. About 100 ml. of acetone was poured in and the flask was then heated on a thermostatically controlled electric heating element. In the preliminary trials the extraction was continued until the thimble was no longer discoloured by the green chlorophyll. Since this time occupied seven hours, extractions for shorter periods were tried and it was found that 87% of the chlorophyll was extracted in one hour, and this time was chosen. The chlorophyll solution was then made up to 100 ml. and diluted as required in order to obtain a reading on the scale of the E.E.L. absorptiometer. Green filter No. 404 was used.

The standard for the uniformity tests was a carefully weighed 50-50 mixture of dried grass meal and ¼" ground barley. It appeared that the barley masked the green coloration to a certain extent as the absorption values were again reduced by 1%.

Cm. dried grass per 100 ml.	E.E.L. Colour Units (404)		
	Dried grass 7 hours	Dried grass 1 hour	D. grass + barley 1 hour
2.0	97.5	77.0	75.0
1.5	73.5	58.1	56.5
1.0	49.0	38.5	37.8
0.75	37.0	28.7	28.2
0.5	25.0	19.4	18.5
0.25	12.5	9.8	9.4

When the quantity of dried grass exceeded 2 grams the extract was diluted until it gave readings in the above range. Multiplying by the dilution factor then gave the true amount present. Three colour tests were made of each sample and the mean taken. Graphic results are shown in Fig.49.

A12. EMPIRICAL CURVES.

Forms of curve.

In order to obtain equations for empirical curves it was necessary to determine the form of the curve in one of the following ways.

1. Straight line curves had the form $y = a + bx$, where a was the intercept on the y axis and b the slope of the line.

2. Power curve, having form

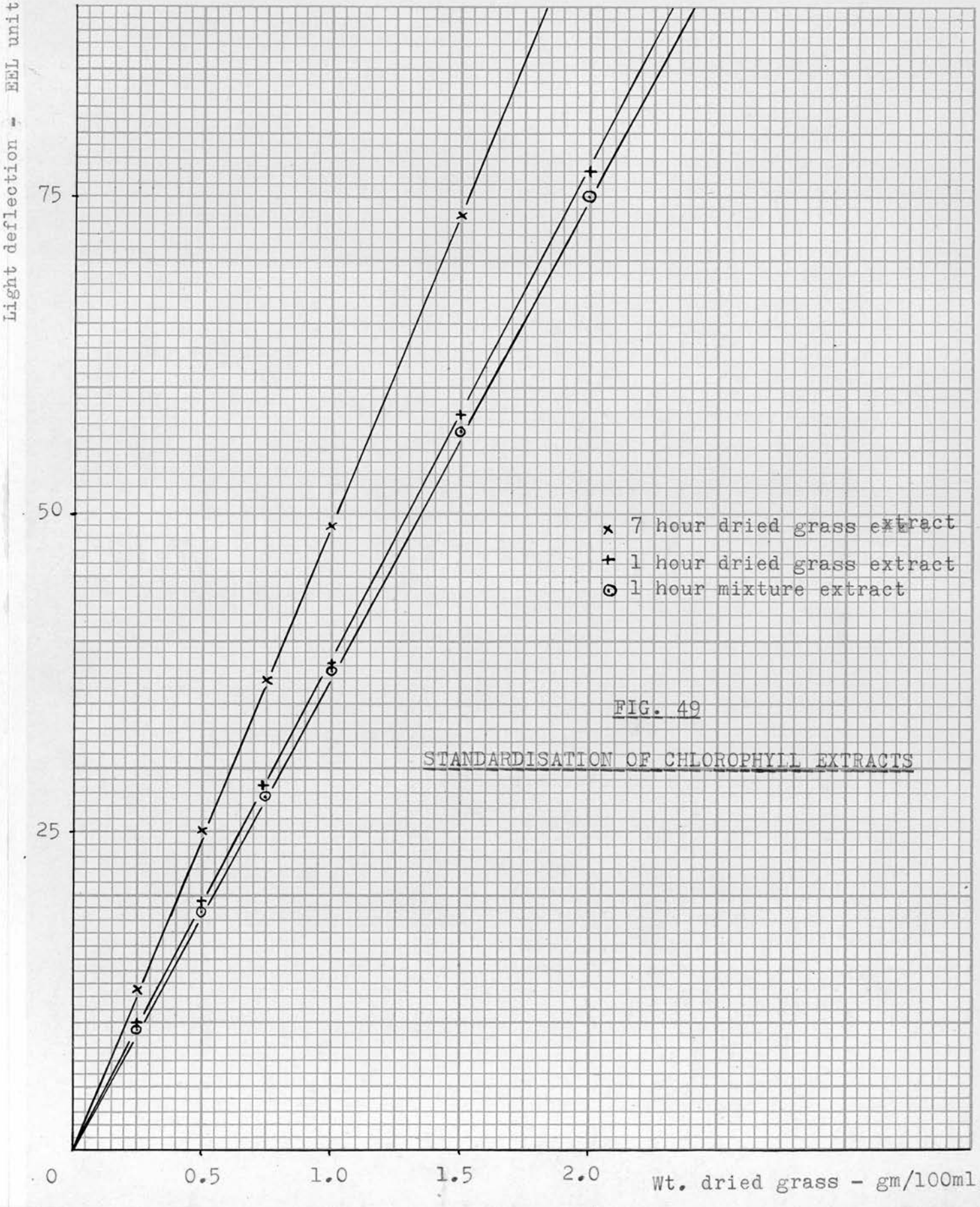


FIG. 49

STANDARDISATION OF CHLOROPHYIL EXTRACTS

2. Power curves had the form $y = ax^b$, when the line went through the origin when b was positive, or was asymptotic to both coordinate axes when b was negative. This relationship gave a straight line of slope b when plotted on a log basis.

3. Exponential curves had the form $y = ae^{bx}$, where x changes in an arithmetic ratio and y in a geometric ratio, therefore plotting log y against x should give a straight line.

4. Logarithmic power curves were parabolic or hyperbolic forms which included additional constants.

5. Logarithmic exponental curves were forms including additional constants which, like the previous case, had to be solved by special equations empirically. The fitting of curves to known data was called rectification.

Probability of Empirical Curves.

The standard procedure for testing the probability of empirical curves was employed, which involved the measurement of the graphical plots from the rectified curve. Obviously the closer the plots to the curve the better the goodness of fit.

The procedure assumed that N was the number of plotted points and m was the number of constants in the empirically derived equation, then the expected number of transitions from the true curve was $\frac{(N - 1) + m}{2}$.

The probability could be obtained from the deviation of the observed number of transitions from the expected using the facter t of Moroney[61]

$$t = \frac{\text{observed value} - \text{expected value}}{\text{standard deviation}}$$

and entering the table of areas of the Normal Curve with each value of t.

A13. Density of Meals.

When calulating the specific surface of meals the true density of the particles was required, however, in the meal form air was incorporated and the density of the mass was reduced, i.e. actually the apparent density.

True density was measured by immersing a known weight of whole grains in water and noting the displacement.

True density experimental data.

Grain etc.	Weight (gm)	Volume (ml)	Grain etc.	Weight (gm)	Volume (ml)
WHEAT	63.7	52.0	STEAM BONE MEAL	31.9	32.0
	22.0	18.5		8.5	9.0
	41.5	33.5		21.8	21.5
	50.9	41.5		20.1	20.5
BARLEY	52.8	48.0	LIMESTONE	68.8	26.0
	15.5	14.0		16.0	7.0
	45.6	41.5		53.3	21.5
	33.0	30.0		41.9	17.0
OATS	52.7	51.5	FISH MEAL	6.7	5.0
	27.9	29.0		25.8	18.0
	31.2	31.0		16.7	12.0
	24.4	25.0		21.0	15.5
MAIZE	22.4	17.0	BUTTER SALT	32.1	13.0
	21.8	16.0		26.8	12.0
	32.5	24.0		12.4	5.5
	25.6	19.0		21.2	9.0
DRIED GRASS	11.6	13.0	BEANS	7.5	5.0
	12.5	14.5		15.7	12.0
	15.4	17.5		22.0	15.5
	14.0	15.0		16.1	11.5
SKIMMED MILK	29.3	20.0	BETA No. 10	18.6	13.0
	10.2	6.5		8.8	7.5
	15.4	10.5		14.5	19.0
	31.6	22.0		15.0	11.5

Some absorption occured with fish meal, skimmed milk and the supplement Beta No. 10.

Particle Shape Investigations.

The particles were examined under a microscope and their dimensions measured by a vernier micrometer. They were then classified according to shape characteristic and the shape constants and specific surface for each was calculated. Due to the large number of readings a special counter was used and the results given below indicate the numbers of particles investigated, along with the maximum, minimum and statistical mean values of each dimension. The values of B, L and T are in microns.

1. True Meals.

	3/16"Milo	3/16"Oats	Dried grass
Total particles	105	333	356
% Tetrahedral	23	5	-
% Prismoidal	56	20	64
% Sub-angular	21	12	7
% Rounded	-	63	29
B - mean	460	442	60
- max	796	830	307
- min	95	77	13
L - mean	602	837	149
- max	1310	2440	612
- min	100	91	21
T - mean	145	219	49
- max	314	462	175
- min	38	41	11
h	3.18	2.12	1.22
n	1.31	1.89	2.49
Standard deviation, h	0.16	0.07	0.15
Standard deviation, n	0.08	0.05	0.10

2. Ground Barley.

	$\frac{1}{4}$" screen	3/16" screen	$\frac{1}{8}$" screen
Total particles	205	199	211
% Tetrahedal	-	2	1
% Prismoidal	10	5	4
% Sub-angular	29	31	27
% Rounded	61	62	68
B - mean	927	625	378
- max	1760	1102	866
- min	181	160	92
L - mean	1232	899	577
- max	2890	2130	1470
- min	177	182	133
T - mean	309	210	122
- max	464	555	444
- min	79	62	15
h	3.02	2.98	3.10
n	1.33	1.44	1.53
Standard deviation, h	0.11	0.08	0.13
Standard deviation, n	0.03	0.03	0.05

3. Other materials.

	Skimmed milk	Salt	Limestone
Total particles	280	189	210
% Tetrahedral	17	-	19
% Prismoidal	44	98	53
% Sub-angular	39	2	26
% Rounded	-	-	2
B - mean	131	305	18
- max	776	840	210
- min	19	22	4
L - mean	261	641	35
- max	1130	998	321
- min	26	47	4
T - mean	52	296	7
- max	217	517	54
- min	8	52	2
h	2.50	1.03	2.52
n	2.01	2.10	1.99
Standard deviation, h	0.09	0.03	0.12
Standard deviation, n	0.04	0.08	0.11

Rectification of d_p and d_l against Surface Factor graphs.

Plotting log S against log dp gave an approximately straight line with a negative slope showing that the curve was that of a hyperbola. The only value not conforming to the straight line rectification was that for ground limestone. (See Fig.50).

Form of equation was:-

$$S = a\,d^{b}$$

For dp:

Intercept, a = .900 cm^2/gm

Slope, b 0.87

Therefore the equation of the graph was:-

$$S = 900\,dp^{0.87}$$

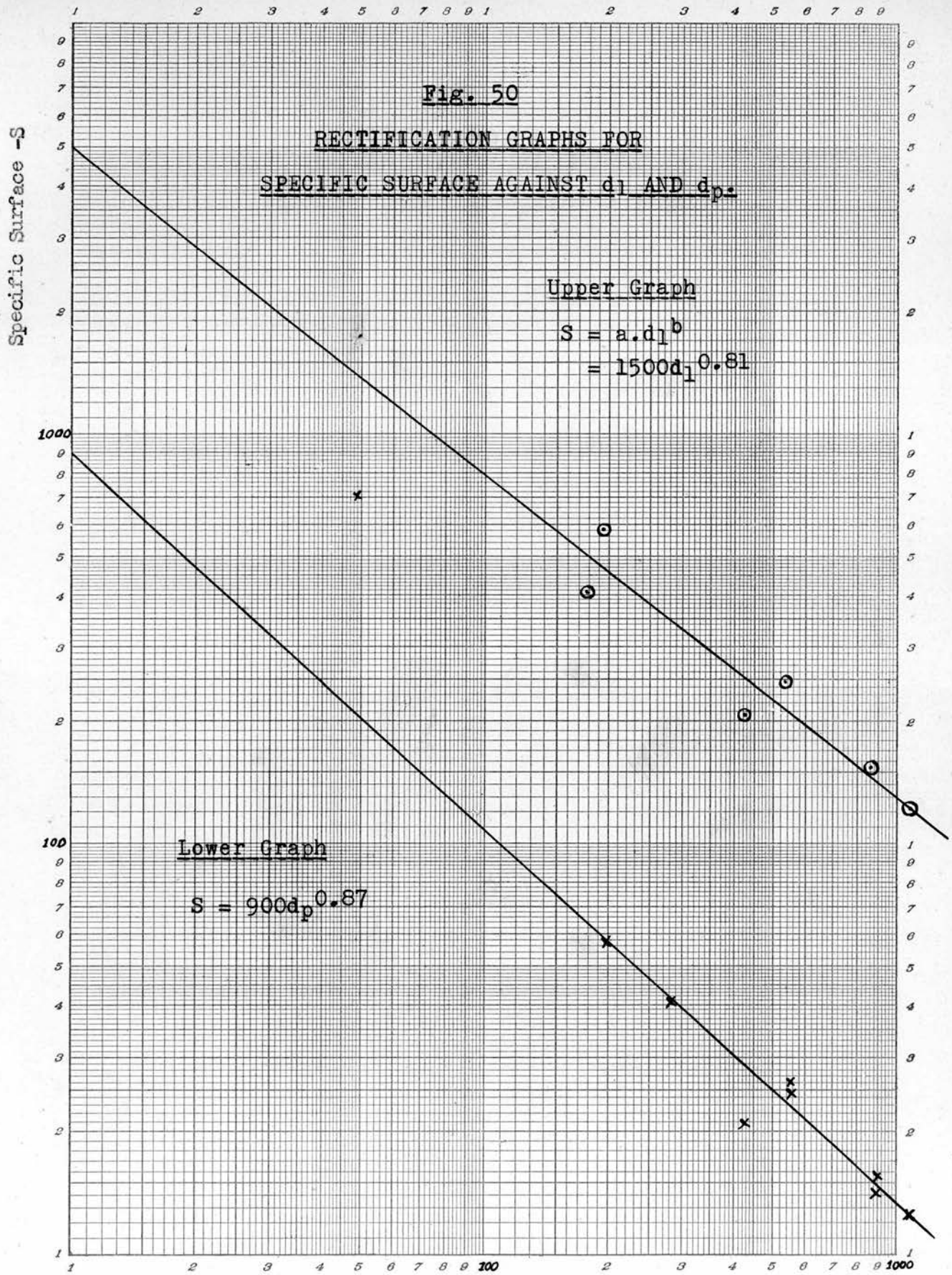
For dl:

Intercept, a = 1500 cm^2/gm

Slope, b = 0.80

Therefore the equation for the graph was:-

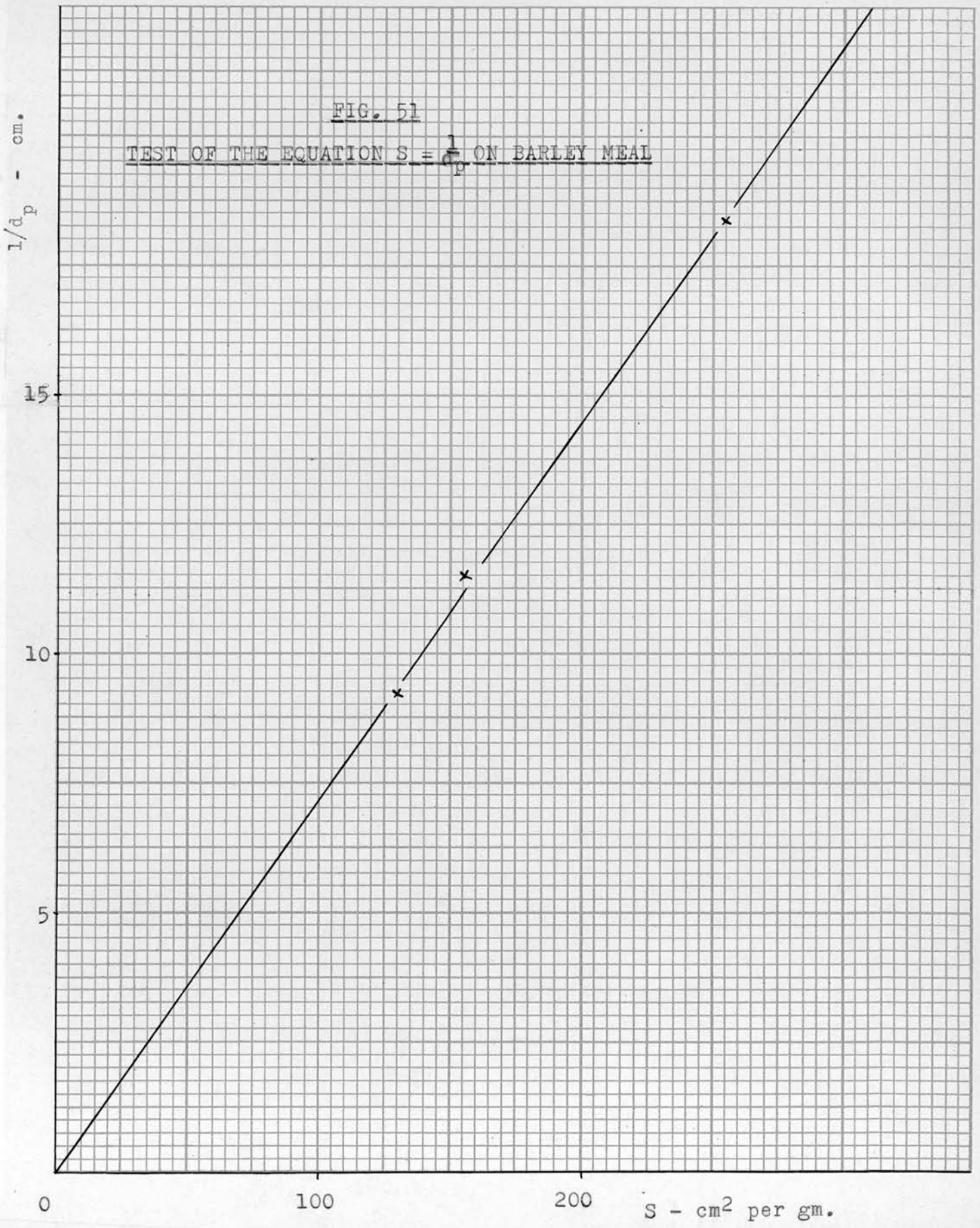
$$S = 1500\,dl^{0.81}$$



DOUBLE LOGARITHMIC (2 CYCLE x 3 CYCLE). HUNT & BROADHURST LTD. OXFORD.

FIG. 51

TEST OF THE EQUATION $S = \frac{1}{d_p}$ ON BARLEY MEAL



The relationship between dp and dl then followed as:-

$$dp = \frac{15}{9} d_l = 1.67 d_l$$

The test of the equation $S = \frac{1}{d_p}$ for different sizes of barley meal is given in Fig.51.

A14. Results of Sieve Analysis of Meals.

Sieves - A.S.T.M. Specification: Endecott woven-wire type.

Shaker - inclined table type vibrator.

Sieving time - 5 mins.

Sample weight - approx. 100 grams.

Meal	Sieve Fraction (gm)						
	4	8	16	30	50	100	Pan
Flaked Wheat	20.1	53.8	20.4	3.1	0.2	0.2	-
	16.9	49.6	26.8	5.7	0.5	0.2	-
	11.7	45.5	31.1	8.9	1.6	1.0	0.2
Broad Wheat Bran	-	14.7	41.7	29.0	8.0	1.7	3.9
	-	17.7	43.2	26.6	5.6	0.8	2.6
	-	19.4	40.9	28.0	5.6	1.9	3.4
Fine Wheat Bran	-	-	-	0.2	35.4	51.1	13.8
	-	-	-	0.3	35.5	53.2	10.8
	-	-	-	0.2	35.4	52.1	12.3
¼" Ground Wheat	-	6.0	35.4	22.9	15.6	14.0	5.2
	-	7.0	41.1	22.4	13.0	9.6	6.7
	-	6.7	38.2	22.3	14.5	11.7	6.6
3/16" Ground Wheat	-	1.9	31.4	28.1	18.7	10.5	9.7
	-	1.5	33.1	26.4	18.6	10.1	10.5
	-	1.7	32.8	27.3	18.0	13.5	5.6
⅛" Ground Wheat	-	0.8	14.5	29.5	22.3	16.3	15.0
	-	0.2	14.8	29.2	22.9	20.0	11.7
	-	0.2	15.8	29.1	22.5	18.6	14.8
1/16" Ground Wheat	-	-	2.6	18.5	29.7	25.2	24.0
	-	-	2.8	18.3	29.0	25.8	24.1
	-	-	3.0	18.1	28.6	26.3	24.0
Crushed Oats	17.0	59.8	16.5	4.5	1.1	1.0	1.7
	18.0	59.2	14.3	4.0	0.9	0.8	2.2
	16.4	60.4	15.5	5.0	1.2	1.3	0.2
¼" Ground Oats	-	6.2	50.4	24.6	8.0	7.8	3.2
	-	7.4	47.9	25.3	8.2	8.6	2.6
	-	4.9	47.5	25.1	8.3	10.6	3.6

Meal	Sieve Fraction (gm)						
	4	8	16	30	50	100	Pan
3/16" Ground Oats	-	1.2	34.5	33.1	22.0	8.1	1.6
	-	1.4	39.6	32.2	12.9	11.5	3.3
	-	2.0	46.5	30.1	11.4	9.8	1.3
⅛" Ground Oats	-	-	9.9	39.6	19.4	25.4	6.3
	-	-	11.8	43.1	23.1	20.9	2.3
	-	-	11.5	42.6	26.2	18.8	1.3
1/16" Ground Oats	-	-	1.0	19.6	35.3	39.8	4.3
	-	-	1.4	20.4	34.7	39.3	4.2
	-	-	1.2	19.9	34.4	39.4	5.1
Flaked Maize	48.2	35.8	10.6	3.7	1.7	1.4	0.9
	45.4	34.6	10.8	3.9	0.6	0.6	0.6
	46.5	34.0	10.1	6.0	1.9	1.3	0.3
Ground Maize	-	-	-	16.1	64.2	21.1	0.4
	-	-	-	17.0	66.4	16.4	0.2
	-	-	-	15.5	55.2	29.0	0.3
¼" Ground Barley	-	11.2	44.2	27.2	11.6	4.8	5.0
	-	10.4	45.2	27.2	10.1	4.5	4.7
	--	10.6	44.7	27.1	10.8	4.1	4.5
3/16" Ground Barley	-	2.0	38.4	33.3	15.0	6.5	4.8
	-	2.3	38.2	33.8	15.2	6.1	4.7
	-	2.1	38.3	33.4	15.9	6.2	4.7
⅛" Ground Barley	-	-	12.0	40.0	27.6	8.9	9.9
	-	-	12.8	41.1	24.0	11.3	8.6
	-	-	16.0	44.7	22.8	10.0	6.5
1/16" Ground Barley	-	-	2.8	19.7	36.7	22.7	18.1
	-	-	3.1	19.5	38.9	22.5	16.0
	-	-	3.5	19.0	37.9	22.4	17.2
Extracted Soyabean Meal	-	-	14.8	44.0	26.4	10.4	4.4
	-	-	14.3	44.7	26.9	9.4	3.8
	-	-	14.5	44.9	26.7	9.8	4.0
¼" Ground Beans	00.2	11.2	39.1	24.8	12.0	5.6	6.9
	1.3	11.3	37.6	26.4	12.8	6.5	7.0
	1.3	11.3	41.2	23.5	10.1	6.2	5.3
3/16" Ground Beans	-	2.3	28.8	30.3	17.0	8.8	13.7
	-	3.0	29.0	26.6	16.2	10.4	15.6
	-	2.5	31.3	28.3	15.7	9.0	13.2
⅛" Ground Beans	-	-	6.9	32.8	25.4	15.8	19.9
	-	0.2	9.8	32.8	24.1	14.3	21.9
	-	0.1	8.7	39.8	23.6	10.0	17.1

Meal (Contd.)	Sieve Fraction (gm)						
	4	8	16	30	50	100	Pan
1/16" Ground Beans	-	-	1.0	13.2	18.8	20.7	46.3
	-	-	0.9	12.9	18.0	21.4	46.7
	-	-	1.5	10.8	23.4	18.4	45.9
Groundnut Meal	-	1.0	4.1	12.5	42.6	37.7	1.8
	-	1.1	3.3	13.0	38.2	42.5	1.6
	-	1.1	3.8	12.7	40.3	40.1	1.8
¼" Ground Milo	-	0.8	16.4	44.5	23.6	13.9	0.8
	-	0.9	18.1	46.0	21.2	11.9	0.4
	-	0.8	13.5	45.2	21.9	17.4	1.6
3/16" Ground Milo	-	0.2	7.5	39.4	23.4	22.7	5.0
	-	0.6	8.9	43.5	27.0	17.7	3.3
	-	0.3	7.0	44.9	27.5	20.0	2.3
⅛" Ground Milo	-	-	3.3	30.5	35.5	14.0	16.7
	-	-	4.2	33.9	33.9	13.7	14.3
	-	-	4.0	30.3	35.3	13.8	16.6
1/16" Ground Milo	-	-	-	16.0	29.1	21.0	33.9
	-	-	1.1	14.8	30.5	20.2	33.5
	-	-	1.6	13.7	30.4	19.8	33.9
Dried Grass Meal	-	-	-	2.1	20.8	50.0	26.1
	-	-	-	1.3	16.5	49.1	31.6
	-	-	-	1.1	20.6	44.8	33.4
White Fish Meal	-	-	3.2	13.9	19.5	33.2	28.2
	-	-	4.5	14.7	19.9	31.6	28.6
	-	-	3.9	14.4	19.8	32.4	28.4
Meat And Bone Meal	-	2.8	22.6	24.8	40.0	10.1	0.2
	-	3.4	25.6	26.8	39.8	4.6	-
	-	3.1	24.1	25.8	39.9	7.3	-
Steam Bone Flour	-	-	-	5.0	10.8	20.1	64.0
	-	-	-	3.2	10.4	18.4	66.6
	-	-	-	4.1	10.5	19.2	65.9
Dairy Minerals	-	-	-	2.0	2.0	36.7	60.8
	-	-	-	2.2	3.7	34.2	59.9
	-	-	-	1.0	1.6	35.5	63.2
Skimmed Milk Powder	-	-	0.4	6.5	42.2	32.8	18.1
	-	-	0.1	5.9	43.0	32.6	18.4
	-	-	0.3	6.2	42.7	32.5	18.3
Whey Powder	-	-	0.4	7.0	23.4	26.8	42.4
	-	-	0.4	6.8	23.0	29.0	40.6
	-	-	0.4	7.1	23.2	28.3	41.0

Meal (Contd.)	Sieve Fraction (gm)						
	4	8	16	30	50	100	Pan
	-	-	-	15.5	35.6	22.5	26.4
Beta No.10	-	-	-	13.5	38.2	23.2	28.7
	-	-	-	12.9	39.2	21.8	28.0
	-	-	-	13.6	41.0	22.8	22.6
Beta No. 8.	-	-	-	10.9	41.3	23.6	23.4
	-	-	-	10.9	41.6	23.6	20.1
	-	-	0.2	12.5	41.2	34.7	11.4
Beta No. 16	-	-	0.6	11.1	39.7	30.8	20.2
	-	-	0.5	10.9	39.8	35.3	14.8
	4.6	15.1	34.3	41.6	6.5	0.2	-
Molassine Meal	8.9	17.0	33.0	40.5	3.4	-	-
	10.1	12.5	37.4	41.5	1.7	-	-
	-	-	-	2.6	88.6	8.8	-
Butter Salt	-	-	-	3.4	92.2	4.4	-
	-	-	-	3.2	90.2	6.6	-

A.15 The relationship between F.M. and size of grinding.

The empirical curves developed in Fig.24 suggested a power relationship between F.M. and the screen hole size, d, of the order

$$F.M. = a(d)^b + c$$

where a,b and c were constants. This was proved by plotting (y - c) against x on logarithmic graph paper and the resultant straight lines were shown in Fig. 52. The slope of the line was b and the equation was hyperbolic because of the negative, or downward to the right, slope. The intercept on the y (F.M.) axis gave the value of a when x = o; c had to be calculated from the equation:-

$$C = \frac{Y_1 Y_2 - Y_3^2}{Y_1 + Y_2 - 2Y_3}$$

in which Y_1 and Y_2 were points on the empirical curves and Y_3 was the ordinate of a point that had an ordinate on the x axis $X_3 = \sqrt{X_1 X_2}$.

$$\log (y-c) = \log a.$$

For the experiments.

$x_3 = 0.177"$ when $x_1 = 0.25"$ and $x_2 = 0.125"$

Wheat

c = - 3.5	y_3 = 2.65
x = $\frac{1}{4}$"	$(y-c)^3$ = 6.45
x = 3/16"	(y-c) = 6.099
x = $\frac{1}{8}$"	(y-c) = 5.65
x = 1/16"	(y-c) = 5.00

Oats

c = 3.6	y_3 = 2.97
x = $\frac{1}{4}$"	$(y-c)^3$ = 6.83
x = 3/16"	(y-c) = 6.60
x = $\frac{1}{8}$"	(y-c) = 5.92
x = 1/16"	(y-c) = 5.33

Barley

c = - 3.8	y_3 = 2.95
x = $\frac{1}{4}$"	$(y-c)^3$ = 7.11
x = 3/16"	(y-c) = 6.81
x = $\frac{1}{8}$"	(y-c) = 6.13
x = 1/16"	(y-c) = 5.52

Milo

c = - 3.8	y_3 = 2.37
x = $\frac{1}{4}$"	$(y-c)^3$ = 6.47
x = 3/16"	(y-c) = 6.19
x = $\frac{1}{8}$"	(y-c) = 5.87
x = 1/16"	(y-c) = 5.12

Beans

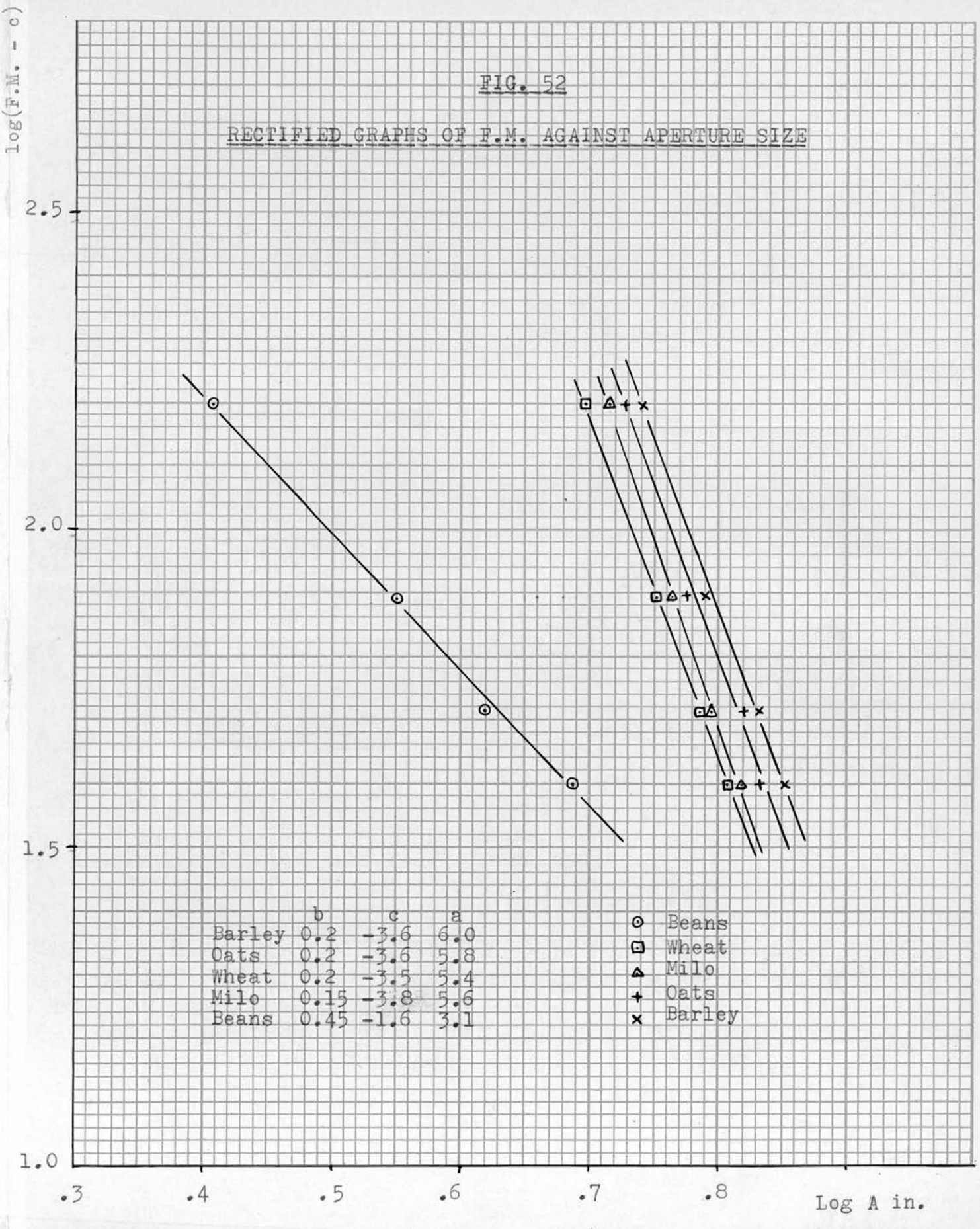
c = - 1.6	y_3 = 2.56
x = $\frac{1}{4}$"	$(y-c)^3$ = 4.76
x = 3/16"	(y-c) = 4.15
x = $\frac{1}{8}$"	(y-c) = 3.55
x = 1/16"	(y-c) = 2.56

Examining the straight lines in Fig. 52 the slope b for the cereal meals was identical and there was a remarkable similarity in the values for the other two constants a and c. The beans differed in all three constant values and milo only in the slope angle which showed that they behaved differently when ground in the hammer-mill.

It was concluded that there was a definite relationship between F.M. and the size of grinding for the conditions of this experiment and the values for the constants are reporduced below.

FIG. 52

RECTIFIED GRAPHS OF F.M. AGAINST APERTURE SIZE



Derived values of the Constants

	a	b	c	Significance
Wheat	5.4	0.20	-3.5	***
Oats	5.8	0.20	-3.6	***
Barley	6.0	0.20	-3.8	***
Milo	5.8	0.15	-3.8	*
Beans	3.1	0.45	-1.6	**

A 16. Angle of repose Results.

Meal	Angle of repose				
Soya bean Meal	55	51	55	59	55
Dried grass Meal	56½	60	61	61	62
Steam bone Flour	69	69	71	67	62
Ground limestone	69	66½	68	67	70
Butter salt	67	70	65	67½	68
Skimmed milk powder	51½	55	54	55	59
Flaked maize	58½	55	57	60	54½
¼" ground maize	57	60	61½	59½	60
Beta No. 10	54½	56	58	56½	56
Crushed oats	49½	55	54	54	57½
¼" ground oats	55	55½	51	49	56
3/16" ground oats	60	61½	54½	61	63
¼" ground barley	53	56	54	55	52
3/16" ground barley	63½	55	60	57	59
¼" ground wheat	49	47	50	51½	55
3/16" ground wheat	53½	59	57½	61	57

50-50 Meal Mixtures.

The standard deviation for each mixture was calculated from the difference of the experimental angles from the average of the sum of the individual angles.

The meals were proportioned by volume and thoroughly mixed in a small rotary drum mixer. A fresh sample was drawn from the batch for each test, the meals being simply poured into the container to prevent any packing effects. Packing had quite a marked effect on the cohesion of particles and in many cases the maximum angle of repose closely

approached 90^0. Results are given in the following table, A and B are the angles for the individual meal in each pair, S.D. the standard deviation and P the probability.

Angle of Repose for mixtures of two meals.

Meal mixture	Angle of Repose^0			$\frac{A+B}{2}$	S.D.	P
¼" ground barley)	56	55	56	57½	2.15	0.03
Dried grass meal)	55	56	56			
¼" ground barley)	58	52½	62	54½	4.07	0.07
Milk powder)	56	53	57			
¼" ground barley)	60	58½	55½	60½	3.07	0.05
Butter salt)	57½	63	59			
¼" ground barley)	56½	54½	52	54	1.58	0.03
¼" ground oats)	54	55	56			
Dried grass meal)	57½	62	59½	61½	2.91	0.05
Butter salt)	63	66	-			
Dried grass meal)	62	62	60	63	2.72	0.04
3/16"ground oats)	68	63	62			
¼" ground oats)	54	58	56	57	1.55	0.03
3/16"ground oats)	58	57	-			
Milk powder)	60½	64½	64	61	2.59	0.04
Butter salt)	64	61	63			

Notation for probability.

P = 10% .....*

P = 5%.....**

P = 1%.....***

A17. The viscosity of Meals.

The rate of flow of a constant volume of meal was timed by automatic stop-clock down a fixed length of pipe viscometer. The moisture content was determined by a Marconi moisture meter and in the moisture content column of the table below the first figure gives the moisture content in Marconi units and the second the moisture expressed as a percentage.

Results for 415 ml. Viscometer.

Meal	Moisture content	Full Scale t sec	Full Scale wt. g.m.	Half Scale t sec.	Half Scale wt. gm.
Flaked wheat	20		144	4.0	187
				3.2	188
	13.9	no flow		3.0	188
				3.8	187
				3.8	188
Broad wheat bran	23.5	6.4	88	3.4	115
		5.8	89	3.4	112
	14.0%	5.0	86	3.4	114
		6.1	92	3.8	115
		5.4	95	3.5	113
Fine wheat bran	21	1.9	176	1.6	187
		2.8	184	1.2	171
	13.8%	2.5	187	1.0	174
		2.6	184	1.1	172
		2.1	179	1.0	172
¼"ground wheat	26	2.0	252	2.5	251
		2.2	251	2.1	256
	14.8%	2.0	261	2.5	254
		2.5	252	2.2	253
		2.0	248	2.3	253
3/16"ground wheat	25	2.2	246	2.9	244
		1.7	243	2.6	253
	14.7%	2.5	258	2.6	255
		2.0	248	2.0	248
		1.7	252	2.0	247
⅛"ground wheat	25	1.9	247	1.7	252
		2.8	255	1.8	254
	14.7%	2.8	253	1.7	250
		3.0	256	1.8	253
		2.5	250	1.8	252
Crushed oats	22		121	7.9	102
		no flow		6.0	89
	13.9%			7.1	90
				9.8	105
				8.5	98
¼"ground oats	36	5.8	144	7.0	140
		5.0	153	5.2	163
	14.8%	4.8	159	6.5	159
		5.6	149	7.3	154
		5.2	159	6.8	152

Meal	Moisture content	Full scale t sec	Full scale wt. gm.	Half scale t sec	Half scale wt gm
		6.5	148	4.4	152
	38	5.5	146	5.5	144
3/16"ground oats	14.6%	5.1	148	5.5	145
		5.0	147	4.8	148
		5.4	150	4.8	145
		4.5	148	3.6	157
	36	4.0	157	3.9	149
⅛"ground oats	14.5%	5.8	154	3.4	159
		5.8	150	3.5	150
		4.8	154	4.6	150
			112		120
	26.5	no flow		no flow	
Flaked maize	12.1%				
		1.2	228	1.0	195
	22.5	1.0	240	1.3	186
Ground maize	14.3%	1.0	230	1.0	182
		1.2	232	1.1	188
		1.0	226	1.0	185
		5.0	252	4.2	214
	25	4.7	241	3.8	223
¼" ground barley	14.3%	4.0	240	3.4	223
		4.8	242	3.5	220
		4.0	244	4.0	225
		3.2	246	3.8	221
	31.5	3.8	245	3.7	222
3/16"ground barley	14.2%	4.5	242	3.3	221
		3.8	244	3.3	223
		3.2	241	3.8	225
		2.5	228	2.2	218
	31.5	3.7	252	3.0	221
⅛"ground barley	14.2%	3.7	246	2.6	225
		2.9	245	2.0	212
		2.2	240	2.0	211
		3.0	283	1.4	264
	40	2.6	265	1.5	265
¼" ground beans	14.6%	2.7	274	2.6	265
		2.6	269	1.5	264
		2.2	277	1.4	258
		2.6	260	2.0	251
	40	2.2	260	2.0	242
3/16" ground beans	14.6%	2.6	259	1.4	242
		2.6	260	1.5	242
		2.3	269	2.1	243

Meal	Moisture content	Full scale t sec	Full scale wt gm.	Half scale t sec	Half scale wt gm.
		1.5	265	2.0	246
	40	2.4	269	1.6	237
$\frac{1}{8}$" ground beans	14.6%	1.4	260	1.4	246
		1.7	269	1.4	246
		2.9	267	1.7	255
		5.0	255	1.3	256
	18	2.8	247	1.3	254
Soya bean meal	9.9%	2.5	248	1.5	255
		2.2	239	1.4	255
		3.3	250	1.3	254
		2.0	278	1.2	255
	27	2.1	289	1.6	250
$\frac{1}{4}$" ground milo	14.7%	1.5	271	1.2	253
		1.5	267	1.4	254
		1.8	278	1.1	250
		2.2	292	1.6	237
	2	1.1	274	1.0	222
3/16"ground milo	14.2%	1.0	267	1.6	240
		2.2	184	1.5	237
		2.0	280	1.2	235
		1.4	279	1.4	232
	26	2.1	280	1.4	239
$\frac{1}{8}$" ground milo	14.6%	1.4	274	1.2	237
		2.0	277	1.2	235
		1.3	272	1.3	236
		1.8	223	1.6	195
	15	1.3	223	2.8	193
Groundnut meal	9.8%	1.8	222	1.5	180
		1.8	223	1.6	191
		1.7	221	1.7	192
			104		199
	35		103		
Dried grass meal	10.2%	no flow		no flow	
		1.0	264	1.0	270
	30	1.0	270	1.2	254
White fish meal	10.8%	1.0	257	1.0	257
		1.3	260	1.0	256
		1.1	266	1.2	253

Meal	Moisture content	Full scale t sec	Full scale wt gm.	Half scale t sec	Half scale wt gm.
		2.0	270	1.5	215
		1.1	257	1.6	230
Meat and bone meal	19.4%	1.8	233	1.8	227
		2.0	248	2.1	230
		1.2	260	1.5	216
		1.0	292	0.7	235
	23	1.0	264	0.8	240
Steam bone flour	10.6%	0.8	277	1.0	245
		1.0	275	0.8	240
		0.8	270	0.8	247
		1.1	392	2.2	353
		1.4	390	2.8	371
Ground limestone	9.5%	1.0	381	2.4	368
		1.0	385	2.0	372
		1.0	400	2.5	365
		1.4	252	1.3	248
		1.2	254	1.1	246
Dairy minerals	9.9%	1.2	255	1.2	242
		1.5	253	1.5	249
		1.3	256	1.2	248
		1.4	139	1.5	162
		2.2	135	1.0	160
Skimmed milk powder	9.5%	1.5	141	1.0	160
		1.5	135	1.5	166
		1.6	136	1.2	164
		3.3	303	2.4	265
		2.2	304	2.8	261
Whey powder	10.1%	5.5	309	5.4	261
		5.2	308	4.8	265
		4.1	308	4.0	263
		1.0	266	1.4	255
		1.0	261	1.5	250
Beta No. 8	11.2%	1.0	264	1.2	252
		1.0	266	1.2	256
		1.1	265	1.0	250
		1.1	330	2.2	299
		1.0	321	1.7	295
Beta No. 10	11.0%	1.0	317	1.0	296
		1.2	320	1.1	295
		1.0	322	1.2	195
		2.0	269	1.0	226
		2.3	272	1.0	230
Beta No. 16	11.3%	1.4	266	1.1	225
		1.5	269	1.5	228
		1.5	268	1.5	232

Meal	Moisture content	Full scale t sec	Full scale wt gm	Half scale t sec	Half scale wt gm
Molassine	20.9%	no flow	163	26.8 28.8 35.5 29.2 26.5	177 175 175 176 175
Butter salt	6.1%	2.1 2.1 2.7 2.4 2.3	466 475 472 475 473	not tested	

Results for 1870 ml. viscometer.

Meal	m.c.	Full scale t sec	Full scale wt gm	Half scale t sec	Half scale wt gm
Flaked wheat	13.5%	24.8 25.3 26.0 25.4 25.2	254 660 662 651 650	- - - - -	- - - - -
Crushed oats	14.3%	40.1 49.6 47.0 45.1 45.0	543 540 539 550 538	- - - - -	- - - - -
Flaked maize	13.9%	7.1 6.7 6.8 7.0 6.9	505 504 505 510 501	5.7 5.9 5.6 5.9 5.9	552 561 553 555 551
Dried grass meal	10.5%	15.2 18.8 18.6 18.6 16.0	457 452 443 447 450	19.3 10.8 18.9 17.1 19.5	842 850 844 840 853
Wheat grains	14.0%	3.2 3.4 3.5 3.2	1418 1415 1416 1418	- - - -	- - - -
		125.0 124.6	733 730	- -	- -

Meal	m.c.	Full scale t sec	Full scale wt gm	Half scale t sec	Half scale wt gm
		125.0	733	-	-
		124.6	730	-	-
Molassine meal		126.7	741	-	-
		132.0	735	-	-
		119.2	733	-	-

A18. Relationship between Viscosity and Specific Surface.

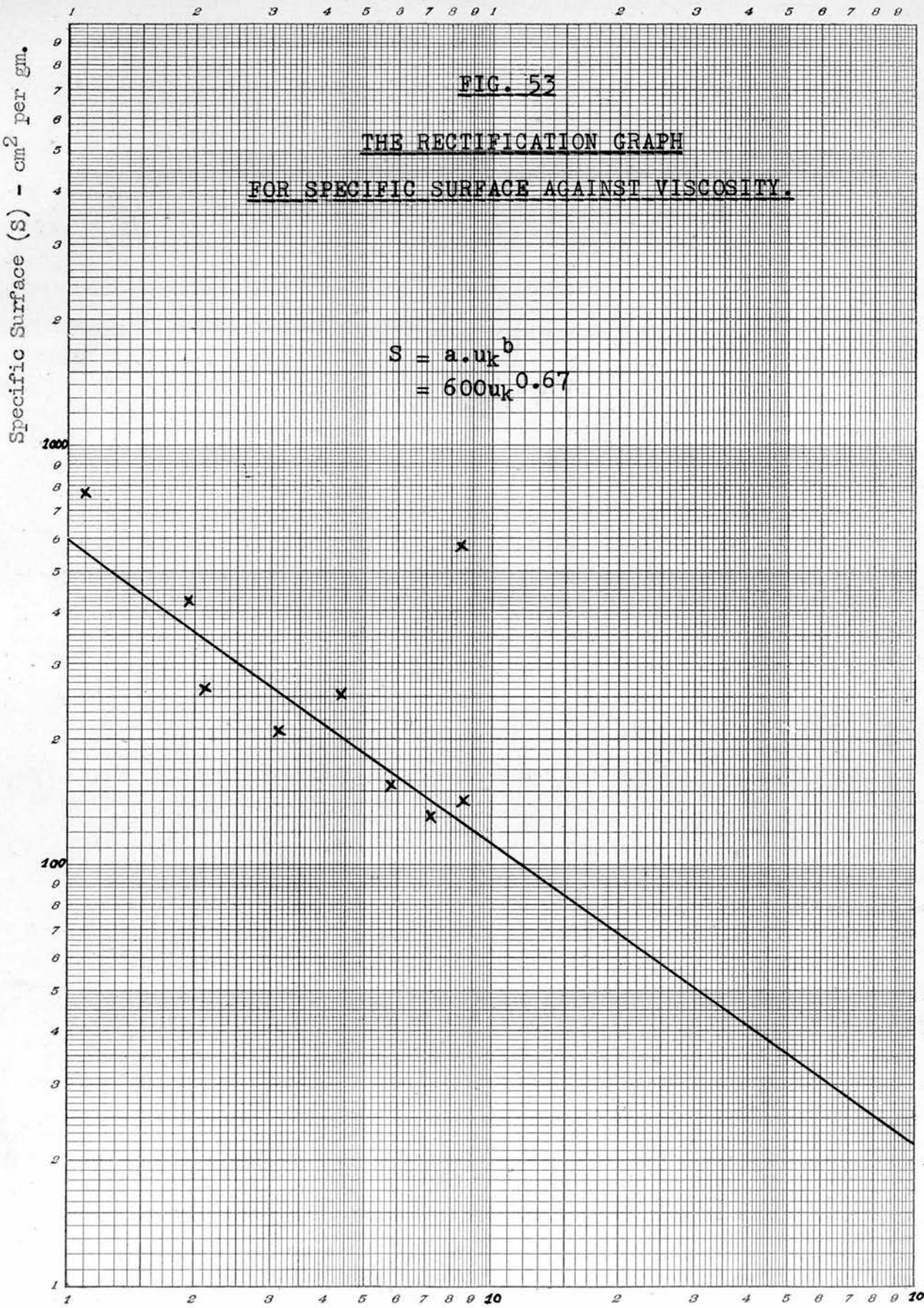
This relationship was studied by plotting the values obtained for kinematic viscosity against those for specific surface of particles. The values below were rectified on log paper in Fig.53 to give a straight line proving a power relationship between U_k and S. Measuring the intercept and the slope of the graph this relationship became:-

$$S = 600\ u_k^{0.67}$$

The plot for dried grass meal was the only one that deviated from this curve to any great extent.

Meal	u_k	S
Ground limestone	1.06	791
Dried grass meal	8.66	587
Milk powder	1.95	415
3/16"ground milo	2.13	262
⅛" ground barley	4.46	250
Butter salt	3.21	211
3/16"ground barley	5.71	153
3/16"ground oates	8.65	145
¼" ground barley	7.15	125

where the units of u_k were cm^2/sec. and S were cm^2/gram.



DOUBLE LOGARITHMIC (2 CYCLE x 3 CYCLE)- HUNT & BROADHURST LTD. OXFORD.

A19. The effect of moisture content on Viscosity of Meals.

Results for ¼" Ground Barley.

Temp.	Moisture content		t	wt
°F	Units	Mean%	sec	gm
72	49.5	19.1%	5.7	220
	50.0		5.4	230
	50.5		5.4	224
			5.0	225
			5.4	226
67	48.0	18.5	4.9	231
	47.5		5.0	226
	47.5		4.7	227
			5.0	228
			4.9	226
67	44.0	17.0%	3.9	233
	45.5		3.9	231
	43.2		3.9	228
			3.7	229
			3.7	230
69	39.5	16.3%	2.9	230
	41.0		3.4	230
	40.5		3.6	228
			3.7	229
			3.4	230
66	27.8	13.5%	2.8	231
	28.0		2.4	225
	29.5		2.3	223
			2.8	225
			2.5	223
68	25.4	12.8%	2.5	230
	26.5		2.4	229
	25.4		2.5	229
			2.3	230
			2.4	228
59	19.0	12.1%	2.2	226
	19.5		2.4	228
	19.0		2.4	226
			2.2	227
			2.4	226
74	14.6	10.7%	2.1	224
	15.5		2.3	230
	16.2		2.0	226
			2.0	225
			2.3	224

Temp.	Moisture content		t	wt
°F	Units	Mean%	sec	gm.
80	-6.0	7.5%	1.8	225
	-6.0		2.3	224
	-6.0		2.2	227
			1.6	225
			2.0	226

Results for ¼" ground wheat

Temp.	Moisture content		t	wt
°F	Units	Mean%	sec	gm
71	47.3	18.7%	4.5	259
	47.4		4.2	256
	46.9		3.9	255
			3.7	252
			3.7	252
68	41.2	17.9%	4.0	264
	41.0		3.7	260
	42.9		3.2	259
			3.4	262
			3.2	260
62	38.5	16.2%	2.9	255
	38.6		2.6	260
			3.0	254
			2.8	254
			2.7	254
59	37.0	15.8%	2.5	261
	37.0		2.9	257
			2.7	255
			2.8	263
			2.7	254
60	34.6	15.0%	2.6	255
	34.0		2.6	251
	36.8		2.4	254
			2.5	250
			2.5	250
60	27.5	13.7%	1.9	262
	27.2		2.2	260
			2.1	258
			2.0	259
			2.9	260
73	26.4	13.0%	2.6	253
	27.0		2.0	255
	26.5		1.6	255
			1.8	258
			2.0	256

Temp.	Moisture content		t	wt
^{o}F	Units	Mean %	sec	gm.
74	20.1	12.5%	2.1	251
	20.2		2.0	254
	19.4		1.7	252
			1.8	254
			1.9	252
81	14.5	10.3%	1.7	255
	15.2		1.7	255
	15.0		1.8	258
			1.9	252
			1.8	251

Rectification of Moisture Content Curves.

The curves suggested a power relationship between moisture content and rate of flow for the two meals. After rectification by the straight line method it was found that they satisfied the equation of a parabola.-

$$y = a + bx - cx^2$$

Selecting coordinates x_1, y_1

$$\frac{y - y1}{x - x_1} = b + cx_1 + cx$$

Since $(b + cx_1)$ was constant, a straight line resulted by plotting $\frac{y - y1}{x - x_1}$ against x.

¼" ground barley

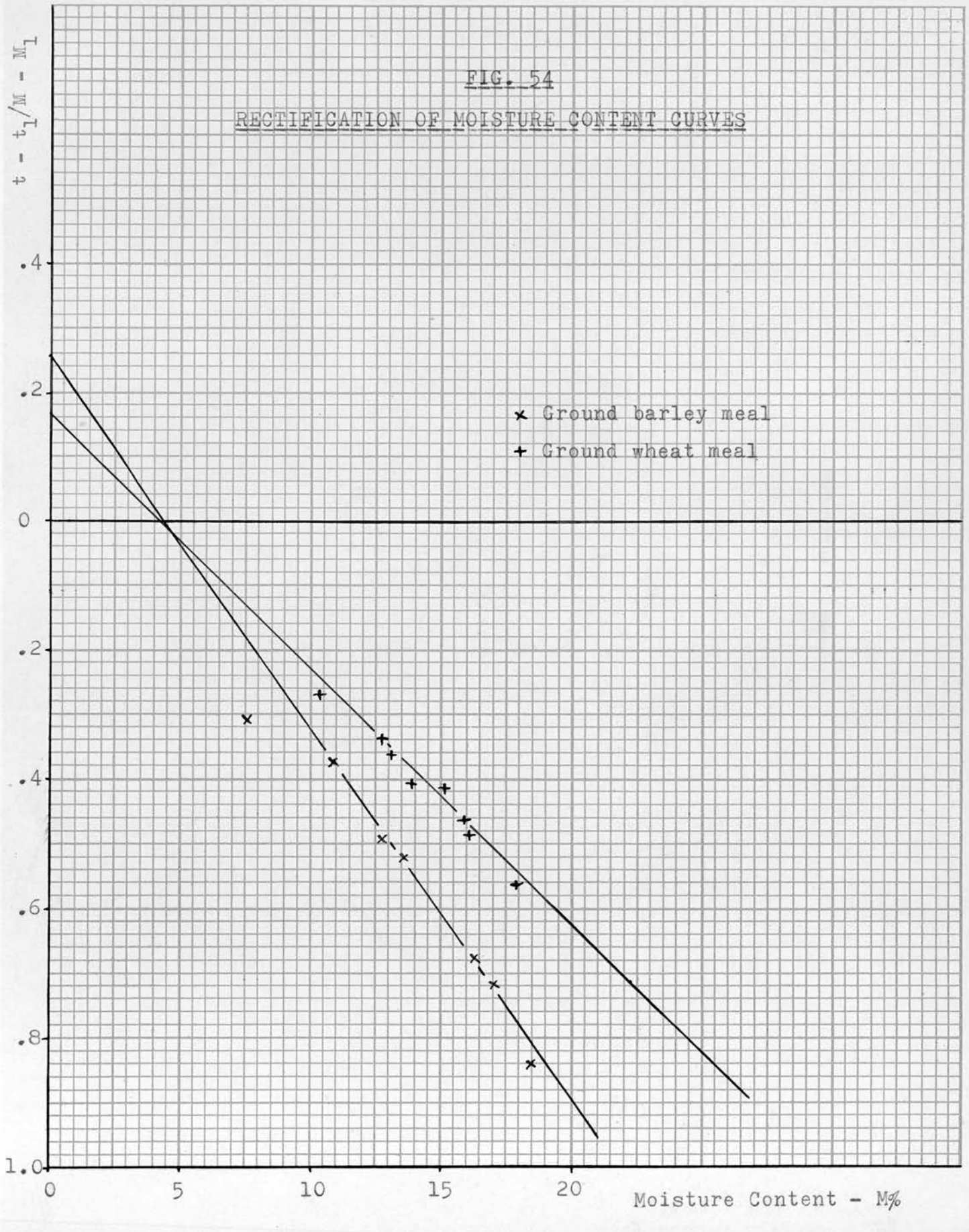
Let $x_1 = M_1 = 19.1\%$

$y_1 = t_1 = 5.4$ sec.

M	$\frac{t - t_1}{M - M_1}$
18.5	- 0.83
17.0	- 0.71
16.3	- 0.67
13.5	- 051
12.8	- 0.48
12.1	- 0.44
10.7	- 0.36
7.5	- 0.29

FIG. 54

RECTIFICATION OF MOISTURE CONTENT CURVES



Rectified these results gave a straight line that crossed the Y axis at 0.25 and had a slope of 1.5; from which the following equation was derived -

$$t = 15 - 28.5M - 1.5M^2$$

<u>¼" ground wheat.</u>

Let $x_1 = M_1 = 18.7\%$

$y_1 = t_1 = 4.0$ sec.

M	$\frac{t - t_1}{M - M_1}$
17.9	- 0.55
16.2	- 0.48
15.8	- 0.45
15.0	- 0.40
13.7	- 0.39
13.0	- 0.35
12.5	- 0.32
10.3	- 0.26

Rectification of these results approximated to a straight line which crossed the X axis at the same value (M = 4.5%) as that for the barley meal. Its slope was 1.0 and the intercept 0.17 from which this equation was derived -

$$t = M^2 - 18.5M$$

A20. <u>Rectification of Uniformity curves relating Model to Full-size Mixer.</u>

<u>(1). 50-50 Dried grass and ¼" Barley meals.</u>

Uniform times were chosen for the model since it would be used in future experiments if satisfactory. Scaling down meant that times for the half-size mixer had to be increased by $\sqrt{2}$ times to keep the scale factor correct. The model capacity was ⅛th that of the full-size mixer and in each case the dried grass was added first.

<u>Model mixer</u>.

Quantity of mix = 112lb. (1 cwt.)

Proportion of dried grass = proportion of barley = 0.5

Amount unemptied from mixer = 4lb.

Sample size = 4 gm. Auger speed = 195 rpm.

Colour units of uniform sample in 100 ml = 76.5

This conforms to the calibration curve in Fig.44 as containing 2 gm. dried grass.

Sample No	Time min.	Wt. Dried grass gm.	Proportion x	Deviation $x - \bar{x}$
A 1	2.0	3.42	.86	.36
		3.36	.84	.34
		0.47	.12	.38
		3.66	.91	.41
		0.28	.07	.43
A 2	4.0	2.80	.70	.20
		0.13	.03	.47
		3.45	.86	.36
		0.72	.18	.32
		3.42	.85	.35
A 3	6.0	2.87	.72	.22
		0.84	.21	.29
		2.82	.70	.20
		0.91	.23	.27
		0.32	.08	.42
A 4	8.0	2.74	.68	.18
		2.79	.70	.20
		0.68	.17	.33
		2.60	.65	.15
		1.16	.29	.21
A 5	10.0	0.68	.17	.33
		0.84	.21	.29
		2.80	.70	.20
		0.75	.19	.31
		1.13	.28	.22
A 6	12.0	0.81	.20	.30
		2.37	.59	.09
		2.34	.58	.08
		0.26	.06	.44
		1.60	.40	.10
A 7	14.0	1.04	.26	.24
		0.46	.12	.38
		1.20	.30	.20
		2.52	.63	.13
		2.78	.69	.19
A 8	16.0	1.01	.25	.25
		0.84	.21	.29
		1.86	.46	.04
		2.48	.62	.12
		1.56	.39	.11

Sample No.	Time min.	Dried grass gm.	Proportion x	Deviation $x - \bar{x}$
A 9	20.0	1.08	.27	.23
		1.08	.31	.19
		1.14	.29	.21
		2.40	.60	.10
		2.60	.65	.15
A 10	25.0	1.18	.29	.21
		1.57	.39	.11
		2.34	.58	.08
		2.52	.63	.13
		1.80	.45	.05
A 11	30.0	1.95	.49	.01
		2.43	.61	.10
		1.02	.25	.25
		1.92	.48	.02
		2.08	.52	.02
A 12	35.0	2.47	.61	.11
		1.61	.40	.10
		1.80	.45	.05
		2.41	.60	.10
		1.92	.48	.02

¼" ground barley	Dried grass meal
14.2% moisture content	10.4% moisture content
3.34 Finenese modulus	0.94 Finenese modulus

The graph showed an exponential relationship between time and the Uniformity index by the straight line method of rectification (see Fig.55). The Y axis was cut at U.I. = 0.85 and the slope was 0.56 giving the equation :-

$$U.I. = 0.85\, e^{0.56t}$$

Full size-mixer

Quantity of mix = 8 cwt.

Amount emptied = 22 lb.

Sample size = 32 gm. Auger speed = 278 rpm.

Colour units of uniform sample in 1 litre = 62.1

This conforms to sample containing 16 gm dried grass.

Sample No.	Time min	wt. dried grass gm	Proportion x	Deviation $x - \bar{x}$
B 1	2.8	10.30	.32	.18
		12.22	.38	.12
		9.60	.30	.20
		20.81	.65	.15
		23.32	.72	.22
B 2	5.7	10.58	.33	.17
		10.72	.34	.16
		21.20	.66	.16
		23.97	.75	.25
		16.80	.52	.02
B 3	8.5	12.28	.38	.12
		11.61	.36	.14
		10.80	.34	.16
		21.16	.63	.13
B 4	11.5	11.62	.36	.14
		10.96	.34	.16
		13.70	.43	.07
		21.75	.68	.18
		15.04	.47	.03
B 5	14.1	11.96	.38	.12
		16.94	.53	.03
		20.16	.63	.13
		11.50	.36	.14
		15.37	.48	.02
B 6	17.0	9.60	.30	.20
		11.09	.35	.15
		12.04	.38	.12
		11.62	.37	.13
		11.98	.37	.13
B 7	19.8	9.36	.39	.11
		11.47	.35	.15
		19.78	.62	.12
		22.11	.69	.09
		12.16	.38	.12
B 8	22.6	11.96	.37	.13
		13.28	.41	.09
		13.21	.41	.09
		19.52	.61	.11
		12.14	.38	.12

Sample No.	Time min	wt. dried grass gm	Proportion x	Deviation $x - \bar{x}$
B 9	28.3	12.30	.38	.12
		15.68	.49	.01
		18.24	.57	.07
		13.75	.43	.07
		18.54	.58	.08
B 10	35.3	18.23	.57	.07
		19.60	.61	.11
		15.34	.48	.02
		16.02	.50	.00
		16.95	.53	.03

¼" ground barley	Dried grass meal
14.1% Moisture content	10.2% moisture content
3.30 Finenese modulus	0.90 Finenese modulus

Rectification again showed an exponential relationship, the straight line cut the Y axis at 0.42 and had slope 0.56 giving the equation

$$U.I. = 0.42\, e^{0.56t}$$

(2). 1-99 Butter salt and 3/16" ground barley

From the previous results it appeared that mixing should be continued for a longer period in the prototype, otherwise conditions were kept the same.

Model Mixer.

Quantity of mix = 112 lb.

Proportion of salt = 0.01 Proportion of barley = 0.99

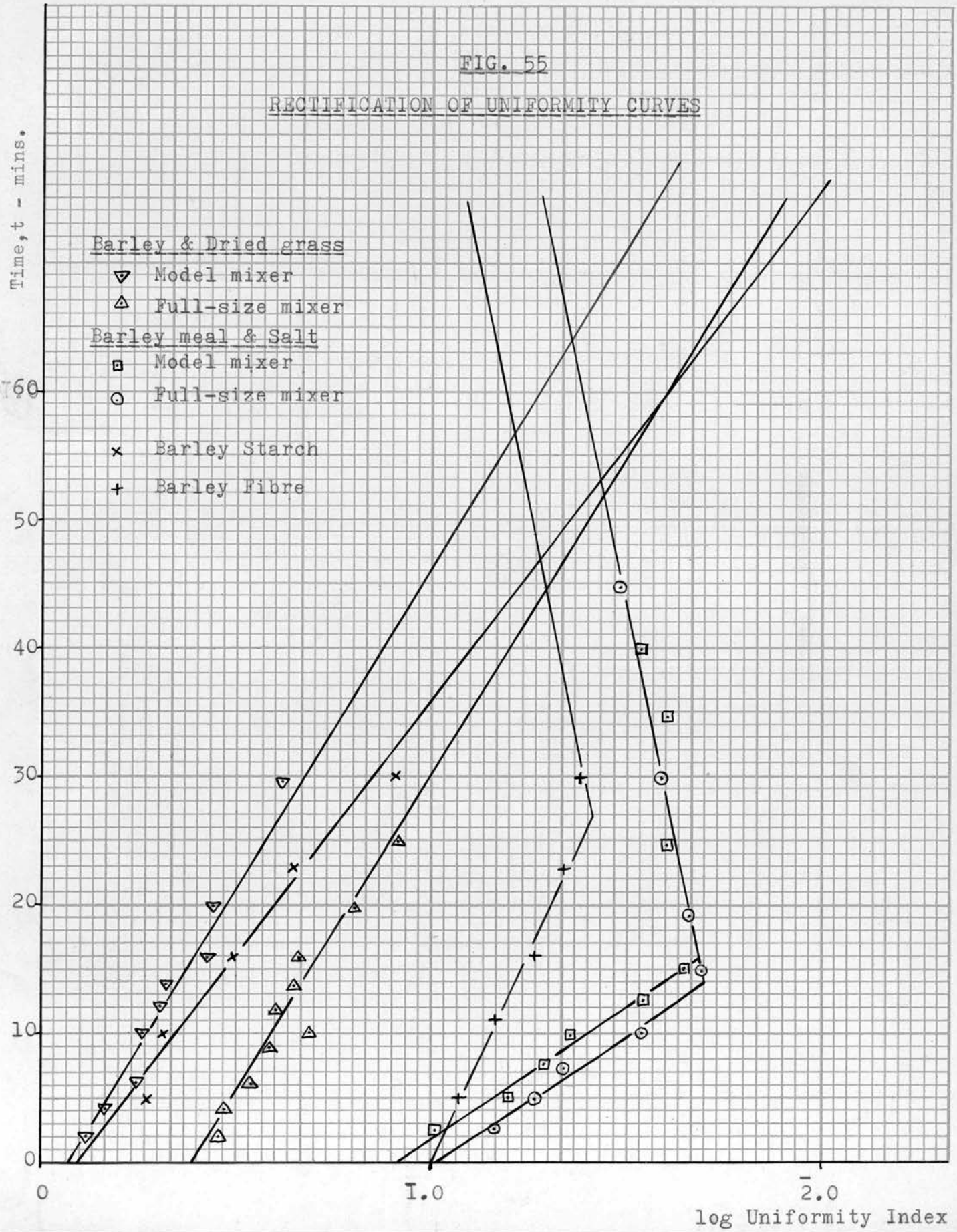
Amount unemptied = 4.5 lb. Sample size = 30 gm.

Auger speed = 194 rpm.

The modified Mohr's method for estimating free chloride was used and the actual proportions of salt present based on standard uniform samples (artificially produced). The mean amount of silver nitrate required for these was 6.0 ml.

FIG. 55

RECTIFICATION OF UNIFORMITY CURVES



Sample No.	Time min	Nitrate ml	Proportion Salt	Deviation
C 0	-	5.92	0.01	-
		6.06		
		6.03		
C 1		0.86	.0018	.0082
		3.22	.0053	.0047
	2.5	0.40	.0009	.0091
		15.04	.0250	.0150
		0.71	.0017	.0083
C 2		2.96	.0048	.0062
		3.53	.0041	.0059
	5.0	0.85	.0018	.0082
		3.30	.0051	.0049
		3.68	.0062	.0038
C 3		5.21	.0087	.0013
		5.69	.0095	.0005
	7.5	3.40	.0057	.0043
		0.32	.0007	.0093
		3.40	.0057	.0042
C 4		3.92	.0067	.0033
		3.29	.0051	.0049
	10.0	3.85	.0064	.0036
		3.52	.0041	.0059
		4.33	.0074	.0026
C 5		4.32	.0072	.0028
		3.81	.0064	.0036
	12.5	5.58	.0093	.0007
		6.01	.0100	.0000
		8.48	.0142	.0042
C 6		3.89	.0066	.0034
		5.00	.0083	.0017
	15.0	6.28	.0105	.0005
		7.41	.0123	.0023
		4.56	.0078	.0022
C 7		4.83	.0080	.0020
		5.17	.0087	.0013
	20.0	4.20	.0070	.0030
		4.99	.0084	.0016
		4.72	.0079	.0021
C 8		5.08	.0086	.0014
		5.98	.0100	.0000
	25.0	3.51	.0059	.0041
		6.74	.0103	.0003
		4.20	.0070	.0030

Sample No.	Time min.	Nitrate ml.	Proportion salt	Deviation
C9		6.67	.0112	.0012
		6.59	.0110	.0010
	30.0	6.21	.0103	.0003
		3.01	.0050	.0050
		4.52	.0074	.0026
C 10		3.44	.0057	.0043
		6.19	.0103	.0003
	35.0	4.80	.0080	.0020
		5.72	.0095	.0005
		4.40	.0076	.0024
C 11		6.41	.0107	.0007
		4.25	.0070	.0030
	40.0	3.93	.0066	.0034
		7.48	.0124	.0024
		4.32	.0073	.0027

3/16" Ground barley

13.9% moisture content

2.99% Finenese modulus

Butter Salt

6.5% moisture content

1.9 Finenese modulus

This graph was a compound one having two slopes, showing that seperation occured after a time. The mixing curve cut the Y axis at o.12 and had a slpe 1.48 giving the exponential equation:-

$$U.I. = 0.12e^{1.48t}$$

Full-size Mixer.

Wt. 3/16" ground barley = 887 lb. wt. salt = 9 lb.

Amount unemptied from mixer = 25.5 lb.

Sample size = 240 gm. Auger speed = 278 r.p.m.

Each sample was extracted with 400 ml. of de-ionised water, filtered and 10 ml. volumes titrated against the standard silver nitrate solution; Standards were tested as before, the mean quantity of nitrate required was 3.66 ml.

Sample No.	Time min.	Nitrate ml.	Proportion salt	Deviation
D O	-	3.28		
		3.62		
		4.10	0.01	
		3.71		
		3.56		

Sample No.	Time min	Nitrate ml.	Proportion salt	Deviation
D 1		1.83	.0050	.0050
		0.89	.0022	.0078
	3.5	2.34	.0064	.0036
		6.87	.0188	.0088
		1.62	.0029	.0071
D 2		2.34	.0064	.0036
		1.53	.0042	.0058
	7.1	1.62	.0044	.0056
		1.67	.0046	.0054
		5.80	.0159	.0059
D 3		1.72	.0047	.0053
		5.56	.0148	.0048
	10.6	2.42	.0066	.0034
		1.90	.0052	.0048
		1.75	.0048	.0052
D 4	14.1	2.38	.0065	.0035
		2.23	.0061	.0039
		3.30	.0090	.0010
		3.15	.0086	.0014
		3.11	.0085	.0015
D 5		2.78	.0076	.0024
		3.00	.0082	.0018
	21.2	2.82	.0077	.0023
		2.96	.0081	.0019
		4.14	.0113	.0013
D 6		2.53	.0069	.0031
		3.26	.0089	.0011
	28.3	2.89	.0079	.0021
		2.67	.0073	.0027
		3.92	.0107	.0007
D 7		3.04	.0083	.0017
		3.32	.0091	.0009
	42.5	2.23	.0061	.0039
		2.56	.0070	.0030
		3.01	.0082	.0018
D 8		2.05	.0056	.0044
		2.81	.0077	.0023
	63.7	4.98	.0136	.0036
		2.59	.0083	.0017

3/16" Ground barley — Butter salt

14.1% Moisture content — 6.7% Moisture content

3.03 Finenese modulus — 1.92% Finenese modulus

Another compound graph resulted with an exponential mixing curve that cut the Y axis at 0.10 and had a slope 1.47, giving the equation :-

$$U.I. = 0.1e^{1.47t}$$

A21. Results of Uniformity experiments with Milk powder and Barley meal.

(1) Bottom-feed with Auger speed = 190 rpm.

Starch Estimation

Sample No.	Time min.	Colour Units Filter 205	Deviation
J O	-	44.0	
		41.3	Mean =
		40.2	41.3
		38.6	
J 1	5	52.4	.266
		27.8	.325
		58.3	.387
		40.0	.025
		48.1	.165
J 2	11	31.5	.236
		49.6	.200
		51.7	.250
		55.4	.320
		48.0	.148
J 3	16	49.0	.188
		46.7	.125
		47.5	.150
		48.0	.170
		49.8	.202
J 4	23	45.1	.088
		46.1	.114
		44.3	.074
		48.7	.185
		44.0	.066
J 5	30	43.7	.063
		39.8	.035
		46.0	.110
		40.2	.022
		42.2	.025

Equation from mixing curve.

$$U.I. = 0.80e^{0.75t}$$

This equation was determined from the rectified graphs in Fig.55.

Normal Acid Fibre Estimation

Sample No.	Time min.	Wt. Fibre gm.	Proportion	Deviation
K 0	-	.444		
		.447	0.20	-
		.469		
		.462		
K 1	5	.594	.260	.060
		.427	.187	.013
		.386	.169	.031
		.431	.189	.011
		.476	.209	.009
k 2	11	.490	.215	.015
		.400	.175	.025
		.344	.151	.049
		.418	.183	.017
		.473	.207	.007
K 3	16	.370	.162	.038
		.427	.187	.013
		.484	.212	.012
		.418	.185	.017
		.432	.190	.010
K 4	23	.514	.225	.025
		.434	.190	.010
		.411	.180	.020
		.414	.181	.019
		.433	.190	.010
K 5	30	.412	.180	.020
		.420	.184	.016
		.472	.207	.007
		.456	.200	.000
		.401	.175	.025

Equation for mixing curve.

$$U.I. = 0.96e^{0.46t}$$

(2) Top-feed with auger speed = 190 rpm.

Sample No.	Time min.	Colour units Filter 205	Deviation
L 0	-	39.3	-
L 1	10	47.0	.175
		42.0	.050
		29.8	.256
		37.7	.062
		37.5	.052
L 2	20	38.3	.036
		41.1	.032
		39.4	.004
		44.1	.102
		47.8	.199
L 3	30	39.6	.010
		42.2	.055
		38.1	.041
		41.0	.026
		39.1	.022

¼" ground barley

Moisture content = 14.0%

Finenese modulus = 3.28

Skimmed milk Powder

Moisture content = 10.0%

Finenese modulus = 1.30

A 22. Results for 20/80 Dried grass and Barley meals.

The experiment was repeated for the bottom-feed and top-feed versions of the model mixer with the following weights of the two mix components :-

Wt. dried grass = 11.2 lb.

Wt. barley meal = 100.8 lb.

Total 112.0 lb.

(1) Bottom-feed with auger speed = 194 rpm.

Sample No.	Time	Wt. D. Grass gm	Proportion	Deviation
G 0	-	0.60	.100	-
G 1	5 min 4	0.25	.042	.058
		0.16	.027	.073
		0.35	.058	.042
		1.32	.220	.120
		0.93	.156	.056
G 2	15 min	0.31	.052	.048
		0.34	.057	.043
		0.26	.043	.057
		0.95	.158	.058
		0.24	.040	.060
G 3	25 min	0.35	.058	.042
		0.37	.062	.038
		0.30	.050	.050
		0.41	.068	.032
		0.85	.141	.041

(2) Top-feed with auger speed = 194 rpm.

Sample No.	Time	Wt. D. Grass gm.	Proportion	Deviation
G 4	5 min	1.39	.231	.131
		0.05	.008	.092
		1.23	.205	.105
		0.01	.001	.099
		1.31	.219	.119
G 5	15 min	0.08	.013	.087
		0.26	.043	.057
		0.22	.036	.064
		0.86	.144	.044
		0.26	.043	.057
G 6	25 min	0.25	.041	.059
		0.36	.061	.039
		0.38	.064	.046
		0.82	.135	.035
		0.22	.037	.063

Sample wt. = 6 gm.

Moisture contents as in Appendix A 28.

A 23. Results of varying auger speed.
(1) 20/80 Milk powder and ¼" Barley meal.

Wt. of mix = 112 lb.

Top feed into mixer

Samples analysed by Iodine Blue Value estimation.

(1) Auger speed = 85 rpm.

Sample No.	Time min.	Colour units Filter 205	Deviation
M. 0	-	40.5	-
M 1	10	24.8	.392
		39.0	.033
		43.3	.075
		48.0	.191
		31.6	.222
M. 2	20	45.9	.128
		45.5	.125
		47.8	.164
		40.5	.000
		35.6	.125

(2) Auger speed = 153 rpm.

Sample No.	Time min.	Colour units	Deviation
N. 0	-	39.2	-
N. 1	10	41.2	.024
		45.4	.125
		46.9	.151
		38.0	.059
		35.9	.111
N. 2	20	44.5	.102
		39.6	.006
		38.8	.007
		45.0	.125
		38.5	.026

(3) Auger speed = 189 rpm. See results for samples L0, L1 and L2.

(4) Auger speed = 262 rpm.

Sample No.	Time min	Colour units	Deviation
P. 0	-	40.3	-
P. 1	10	49.0	.217
		42.4	.052
		47.3	.261
		37.0	.089
		29.1	.277
P. 2	20	39.4	.023
		41.9	.035
		33.8	.161
		46.3	.150
		32.4	.202

(5) Auger speed = 352 rpm.

Sample No.	Time min.	Colour units	Deviation
Q. 0	-	40.0	-
Q. 1	10	49.5	.225
		53.5	.312
		46.0	.154
		59.4	.475
		28.8	.280
Q. 2	20	45.8	.126
		56.9	.514
		44.8	.195
		45.0	.200
		31.4	.215

¼" ground barley

Moisture content = 14.2%

Finenese modulus = 3.33

Skimmed milk powder

Moisture content = 9.9%

Finenese modulus = 1.31

(2) 1/99 salt and ¼" Barley meal

Wt. of mix = 112 lb.

Bottom-feed into mixer using shrouded auger.

Samples analysed by the Free Chlorine method and withdrawn by the sampling spear after 20 minutes mixing

in each speed test.

Sample No.	Auger speed r.p.m.	Nitrate ml	Salt propn.	Deviation
R. 1	86	3,01	.0050	.0050
		1,62	.0027	.0073
		7,54	.0125	.0025
		2,64	.0044	.0056
		4,20	.0070	.0030
R. 2	152	4,62	.0077	.0023
		7,32	.0122	.0022
		7,51	.0125	.0025
		5,10	.0085	.0015
		4,98	.0083	.0017
C. 7	194	4,83	.0080	.0020
		5,17	.0087	.0013
		4,20	.0070	.0030
		4,99	.0084	.0016
		4,72	.0079	.0021
R. 3	265	14,49	.0241	.0141
		0,66	.0011	.0089
		7,86	.0131	.0031
		2,22	.0037	.0063
		0,96	.0016	.0084
R. 4	350	13,09	.0218	.0118
		28,77	.0479	.0379
		0,30	.0005	.0095
		0,67	.0011	.0089
		45,41	.0755	.0655

Ground barley meal

13,9% Moisture content
2,99 Finenese modulus

Butter salt

6,5% Moisture content
1,91 Finenese modulus

Sample size = 30 gm.

A 24. The effect of varying the Mixing Chamber Size.

20/80 Milk powder and ¼" barley meal

Wt. of mix = 112 lb.

Top-feed version of the model mixer was used and the mixing performed with a shrouded auger at 190 rpm. Each test mix was sampled after 20 minutes mixing.

Mean colour units = 40.0 when deviation = 0.

Sample No.	Chamber size	Colour Units	Deviation
L4	24" x 22"	45.0	.123
		36.2	.094
		46.5	.142
		33.8	.161
		32.5	.184
L5	21" x 22"	43.2	.085
		38.9	.037
		42.6	.071
		34.5	.136
		43.0	.078
L2	18"x 22"	38.3	.036
		41.1	.032
		39.4	.004
		44.1	.102
		47.8	.199
L6	15" x 22"	41.6	.047
		39.2	.028
		41.2	.041
		36.7	.075
		37.5	.049
L7	12" x 22"	36.6	.074
		38.3	.049
		37.1	.063
		38.4	.046
		41.2	.041

Ground barley meal
13.9 % moisture content
3.28 Fineness modulus

Skimmed milk powder.
10.0% moisture content
1.30 Fineness modulus

A 25 The effect of shrouding the mixing auger.
20/80 milk powder and $\frac{1}{4}$" barley meal.

(1) Un-shrouded auger.

Wt. of mix. = 112 lb.

Top-feed version of model mixer

Auger speed = 190 rpm.

Mean colour units = 39.9 when deviation = 0

Sample No	Time mins.	Colour Units	Deviation
L8	10	44.6	.114
		35.1	.120
		47.0	.171
		47.8	.201
		34.1	.147
L9	20	38.4	.046
		42.7	.076
		38.4	.046
		43.7	.091
		36.4	.087
L10	30	40.1	.009
		38.9	.033
		41.0	.030
		37.3	.059
		40.8	.028

(2) Shrouded auger.

The results from sample numbers L1, L2 and L3 were used as a comparison from Appendix A 22.

A 26 The effect of spreading blades on the mixing auger.
20/80 Milk powder and $\frac{1}{4}$" ground barley

(1) With spreading blades.

Wt. of mix = 122 lb.

Top-feed version of the model mixer.

Auger speed = 190 rpm.

Shrouded auger.

Mean colour units = 39.9 for zero deviation.

Sample No.	Time mins.	Colour Units	Deviation
L11	10	44.2	.103
		38.9	.033
		42.9	.081
		35.2	.118
		34.0	.152
L12	20	38.2	.036
		36.4	.090
		42.4	.064
		38.6	.045
		41.4	.049
L13	30	40.1	.008
		39.3	.026
		40.8	.028
		37.9	.041
		41.1	.033

(2) Without spreading blades

Data as for sample numbers L1, L2, and L3 from the experiment in Appendix A 22.

A 27 Results of varying the proportion of dried grass in a mix.

(1) 5% Dried grass

Wt. of dried grass = 5.6 lb

Wt. of Barley meal = 106.4 lb.

Total 112.0 lb.

Sample size = 10 gm. Auger speed = 190 rpm.

Sample No.	Time	Wt. D. Grass gm.	Proportion	Deviation
F0	-	0.50	.050	-
F1	5 min	0.43	.043	.007
		0.76	.076	.026
		0.52	.052	.002
		0.74	.074	.024
		0.44	.044	.006
F2	15 min	0.37	.037	.013
		0.58	.058	.008
		0.44	.044	.006
		0.36	.036	.014
		0.74	.074	.024
F3	25.min	0.48	.048	.002
		0.25	.025	.025
		0.48	.048	.002
		0.39	.039	.011
		0.60	.060	.010

(2) 25% Dried grass.

Wt. of dried grass 28 lb.

Wt. of barley meal = 84 lb.

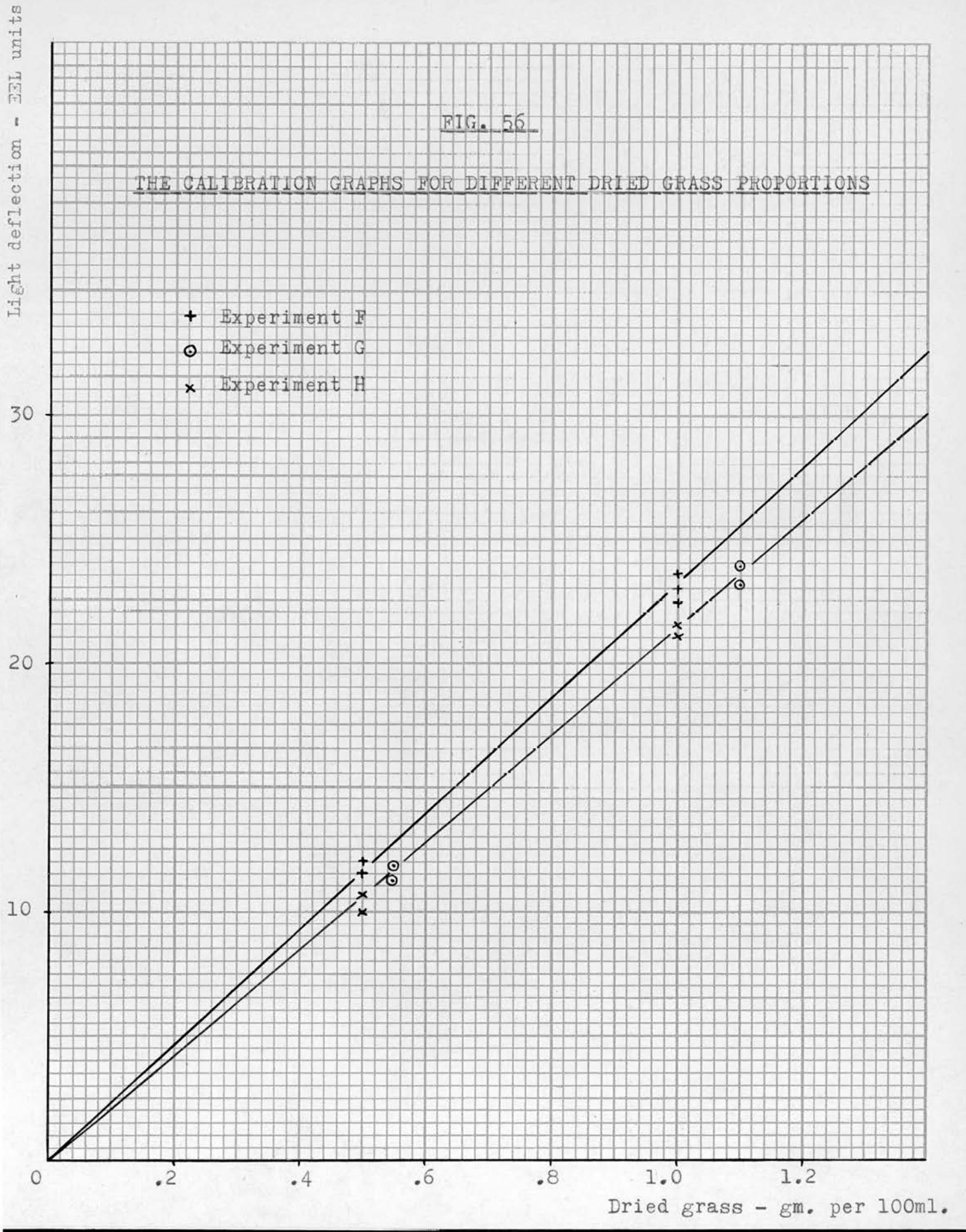
Total 112 lb.

Sample size 4 gm. Auger speed = 190 rpm.

Sample No.	Time	Wt. D. Grass gm.	Proportion	Deviation
H0	-	1.00	.250	-
H1	10 min	0.25	.062	.188
		0.16	.040	.210
		0.61	.153	.097
		1.32	.330	.080
		0.55	.138	.112
H2	20 min	0.35	.088	.162
		0.41	.103	.147
		0.51	.127	.123
		1.20	.300	.050
		0.68	.170	.080
H3	30 min	0.75	.187	.063
		0.78	.195	.055
		1.15	.287	.037
		0.58	.146	.104
		0.63	.159	.091

FIG. 56

THE CALIBRATION GRAPHS FOR DIFFERENT DRIED GRASS PROPORTIONS



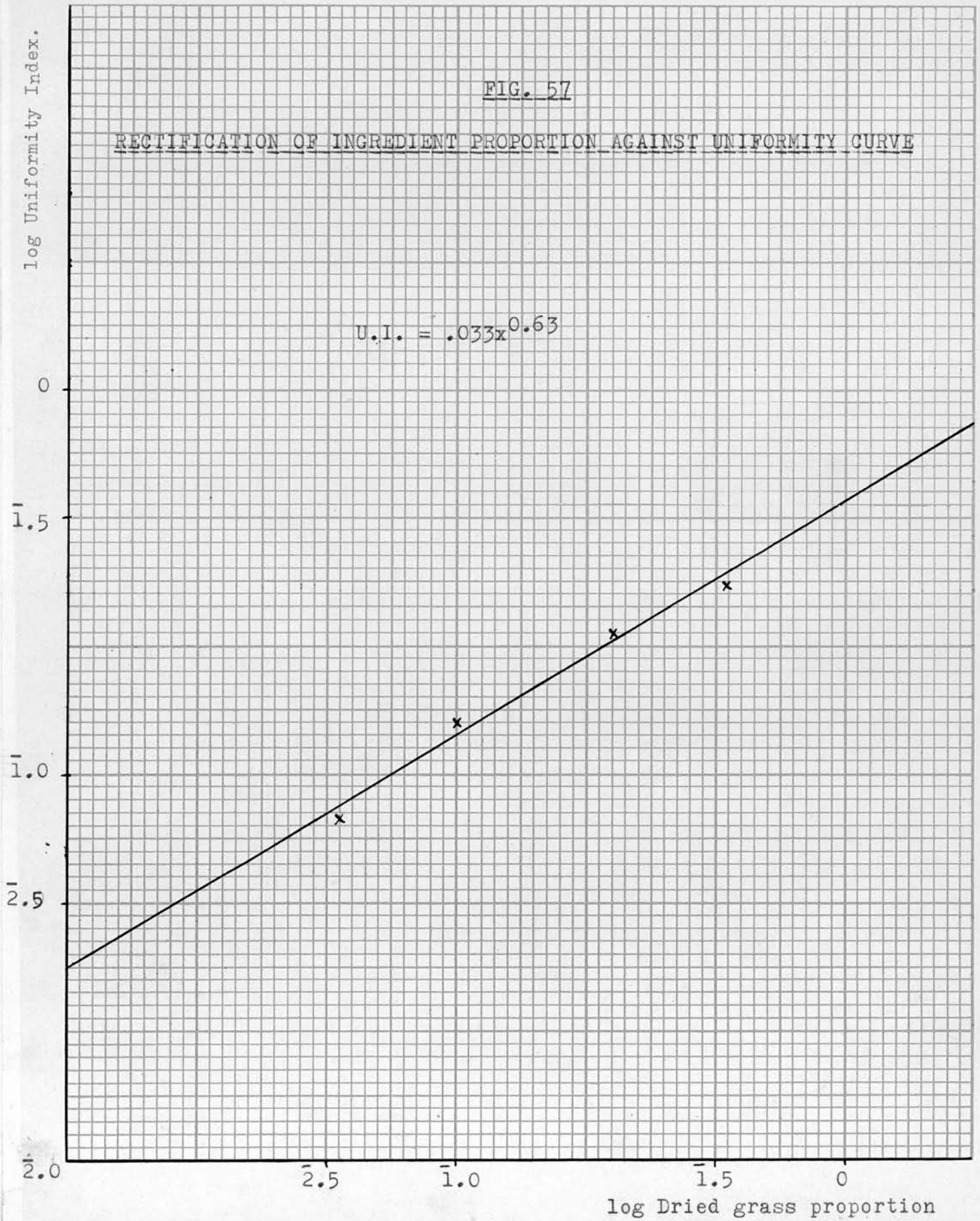


FIG. 57
RECTIFICATION OF INGREDIENT PROPORTION AGAINST UNIFORMITY CURVE
U.I. = .033x^0.63
log Uniformity Index.
0
1.5
1.0
2.5
2.0
2.5
1.0
1.5
0
log Dried grass proportion

A 28 Results of 20% Salt mixes.

Time = 20 mins. Auger speed = 190 rpm.

Sample size = 5 gm. analysed by Mohr's halide estimation.

Bottom-feed into the model mixer.

20/80 Salt and ¼" Barley		20/80 Salt and 3/16" Barley	
Proportion Salt	Deviation	Proportion Salt	Deviation
.149	.051	.179	.021
.224	.024	.212	.012
.165	.035	.200	.000
.165	.035	.169	.031
.169	.031	.168	.031

20/80 Salt and dried grass meal	
Proportion Salt	Deviation
.159	.041
.164	.036
.227	.027
.145	.055
.245	.045

A 29 The mixing of three ingrdients.
1/10/89 mix of salt, dried grass and ¼" barley meals.

The bottom-feed version of the model mixer was used with a mixing speed of 192 rpm. using the shrouded auger. Each sub-sample of meal weighed 6 gm. and it was tested in turn for halide, starch and chlorophyll content by the standard procedures.

(1) 1% Salt analysis.

Time	Nitrate ml.	Proportion salt.	Deviation
10 mins.	2.64	.0044	.0056
	3.30	.0055	.0045
	1.75	.0029	.0071
	9.00	.0150	.0050
	3.02	.0050	.0050
20 mins.	2.16	.0036	.0064
	4.31	.0072	.0028
	3.66	.0061	.0039
	7.56	.0126	.0026
	4.31	.0072	.0023
30 mins.	2.10	.0035	.0065
	0.96	.0016	.0084
	3.72	.0062	.0038
	7.32	.0122	.0022
	2.70	.0045	.0055
40 mins.	10.81	.0018	.0082
	3.18	.0053	.0047
	2.34	.0039	.0061
	0.30	.0005	.0095
	7.87	.0131	.0031
50 mins.	12.91	.0215	.0115
	14.48	.0241	.0141
	2.52	.0042	.0058
	2.04	.0034	.0066
	0.30	.0005	.0095

(2) 10% Dried grass meal analysis.

Time	Gm. wt. Dried Grass	Proportion	Deviation.
10 mins	1.11	.185	.085
	0.33	.051	.049
	0.24	.040	.060
	1.03	.171	.071
	0.81	.135	.035
20 mins	0.99	.165	.065
	0.52	.086	.014
	0.29	.048	.052
	0.34	.056	.044
	0.81	.137	.037
30 mins	0.36	.044	.056
	0.54	.090	.010
	0.70	.117	.017
	0.29	.047	.053
	0.40	.067	.033
40 mins	0.64	.107	.007
	0.29	.049	.051
	0.50	.083	.017
	0.48	.080	.020
	0.44	.074	.026
50 mins	0.77	.126	.026
	0.62	.104	.004
	0.47	.078	.022
	0.50	.083	.017
	0.60	.100	.000

(3) Barley meal analysis

Time	Colour Units	Deviation
10 mins	31.6	.224
	54.5	.267
	41.0	.162
	47.7	.259
	38.9	.025
20 mins	47.6	.164
	46.0	.125
	39.6	.021
	51.1	.250
	49.4	.222
30 mins	38.6	.030
	35.3	.134
	40.2	.008
	45.1	.112
	39.4	.022
40 mins	40.4	.006
	38.7	.029
	40.7	.004
	41.5	.008
	39.0	.024
50 mins	40.3	.007
	41.5	.008
	41.1	.006
	39.9	.013
	41.5	.008

Colour units when deviation was zero = 40.9.

A 30 **The Uniformity of a Complete Poultry Food.**

Three 130 gm samples were withdrawn by the beaker method whilst the mix was being discharged from the mixer and the complete analysis of each sample is shown below.

First Batch.

Chemical Component	Uniform %	Sample %		
Protein	16.4	17.6	17.6	15.1
oil - ether extract	4.3	4.4	4.4	4.3
Fibre	5.3	5.5	5.7	5.3
Nitrogen - free extract	53.1	50.7	50.5	55.1
Mineral matter	8.8	8.6	9.4	7.3
Moisture	12.1	13.2	12.4	12.9

Second Batch.

Chemical Component	Uniform %	Sample %		
Protein	16.4	17.3	16.2	16.1
oil - ether extract	4.3	4.3	4.5	4.3
Fibre	5.3	4.6	5.2	5.2
Nitrogen - free extract	53.1	52.5	53.4	53.5
Mineral matter	8.8	9.3	8.9	8.6
Moisture	12.1	12.0	11.8	12.3

A 31 Results of Pig Feeding Experiment.

Age weeks.	Uniform Mix. Pig weights (lb.)	Non-uniform Mix. Pig weights (lb.)
12	82.4	81.9
	83.3	84.5
	75.1	76.7
	77.6	76.3
	77.1	77.6
13	91.1	90.6
	92.0	93.2
	85.2	84.7
	85.4	84.4
	83.8	85.5
14	99.6	98.3
	99.9	101.5
	93.7	92.4
	93.8	92.0
	92.6	94.8
15	108.3	106.9
	107.7	109.8
	102.3	99.9
	102.6	99.6
	101.5	103.1
16	116.4	115.1
	116.0	117.8
	111.8	107.5
	112.7	107.3
	111.1	111.3
17	125.7	123.2
	125.3	125.8
	119.7	114.6
	120.8	114.1
	119.1	117.2
18	135.8	131.0
	135.8	133.5
	129.3	122.7
	130.0	122.6
	129.2	127.4

Statistical Analysis.

Component	Age of pigs in weeks.						
	12	13	14	15	16	17	18
Sum of Squares							
Treatments	0.22	0.12	0.02	2.03	8.50	27.82	52.73
Error	103.26	116.40	117.94	123.65	109.88	150.53	143.01
Total	103.48	116.52	117.96	125.68	118.38	178.35	195.74
Mean Squares							
Treatments	0.05	0.02	0.00	0.50	2.15	6.98	13.18
Error	20.65	23.28	23.59	24.71	21.97	30.11	28.60
F	0.002	0.001	0.000	0.021	0.098	0.233	0.461

Values of F.

6.26 at 5% level of significance.

15.52 at 1% level of significance.

obtained from Fisher and Yates [63] "Statistical Tables."